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AN EVALUATION OF THE ENVIRONMENTAL IMPACT REDUCTION IN THE URBAN DELIVERY LOGISTICS USING TRYCICLES: A CASE STUDY IN PORTLAND, OR, USA

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PRESENTATION

El siguiente proyecto final de carrera está basado en la investigación que desarrollé durante el pasado año en Portland State University (Portland, Oregon, USA).

Gracias a Javier Faulin, mi Profesor y Tutor en la Universidad Pública de Navarra, conseguí contactar con Miguel Figliozzi (Portland State University), quién fue mi mentor durante Marzo y Diciembre de 2015 en el Transportation Technology and People (TTP) research group, en el Maseeh College of Engineering & Computer Science, de Portland State University.

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1. INTRODUCTION

1.1 Transportation Engineering

Transportation is the movement of goods and people from one place or location to another place. The main modes of transport are air, road, rail, water, pipeline, space and cable. Transportation is also called transport, and it is important because it allows trade between people and companies, which is very important for the development of civilizations and cities. The transportation business has been one of the greatest growing activities over the last two centuries due to the world's development and industrialization, which increases trade and human movement inside a country (nationally) and between different countries (internationally). The great technical advances and new technologies have been developed the transportation field and has resulted in more efficient, faster and bigger vehicles, and lower transportation costs.

Transportation science or transportation engineering is the application of scientific knowledge and new technologies to the planning, design, operation and management of facilities for all modes of transportation, with the goal of providing efficient, rapid, comfortable, safe, economical, convenient and environmentally sustainable movement of goods and people. It is a sub-discipline of industrial engineering and of civil engineering.

Freight transportation is the movement of commodities and merchandise goods an cargo and all the processes involved in these activities. The term shipping is referred originally to the transportation by sea or water, but it is extended in American English to refer to transport of people and goods by land, rail or air as well. The term "logistics" is borrowed from the military field, is also used in the same meaning. Logistics is defined as the detailed organization and implementation of a complex operation of freight movement. In a more general business sense, logistics is the management of the flow of items between the point of origin and the point of consumption or final customer with the aim of meeting customers' requirements and necessities. The logistics of physical things includes the integration of information flow, production,

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materials, packaging, transportation of things, inventories, warehousing and security. In this context, logistics management is defined as the part of the supply chain management that plans, implements and controls the effective and efficient flow of goods from the point of origin to the final point, storage, and other services and information needed to the better knowledge in order to meet customer's requirements. The complexity of logistics activities can be analyzed, modeled, showed and optimized by dedicated simulation software. The minimization of the use of resources is a common motivation in all logistics fields. Here we explore the usage of electric vehicles (tricycles) in order to minimize the environmental impact while the process of urban distribution of goods.

The distribution system needs to fit some environmental, economic and social changes, needs to meet several requirements and it has to take into account some basic characteristics. Since the transport of goods is a central element of the economic development, it has an important role in our society. Currently, road transport or terrestrial transport is the principal mode used by governments and companies but at the same time is the most criticized, because of the negative environmental impact.

1.2 Urban freight distribution externalities

Urban freight distribution refers to freight transportation and distribution within urban areas. Urban freight distribution includes a lot of diverse stakeholders, both with the actors in the supply chain we mentioned above, and those stakeholders within the urban area that are no directly involved in the goods movement (residents, city authorities, visitors). The former is categorized according to the supply of goods (producers and shippers), the transportation of those goods (transport operators) and the demand of goods (receivers).

The demand of urban transportation of goods has increased during the last century due to the concentration of the population in cities or urban areas. According to a United Nations report launched in 2014, 54% of world's population now lives in urban areas [1]. In United States, over 80% of the population already lives in urban areas (United States Census, 2012) [2]. Most of the industrial production is delivered in urban areas,

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so urban freight distribution efficiency is a key factor because the distance involved in it has risen over the last decades.

In this context, we have to deal with a specialization of the urban and economic system, with a global division of production and its associated freight. The population density and the large variety of supply chains offering a wide range of economic activities that characterized a city demonstrate the necessity of an efficient, intense and frequent freight urban distribution system that require an improvement of the terrestrial transport, to respond to citizens' necessities. The interaction between the different stakeholders mentioned above increases the complexity of the search for solution to achieve sustainable urban distribution. The case is presented here: Since logistics decisions are taken on the basis of a commercial, economic and operational factors instead of considering sustainability issues concerning city authorities, residents or visitors; solutions are complex and it is impossible to please all stakeholders.

Urban distribution of goods is a key element to the correct functioning of urban economies since it is required, for instance, to replenish stocks of food and other retail goods in shops, deliver documents, parcels and other supplies to offices and to remove household waste from urban residence and office areas [3].

As stated before, cities need more than ever to be sustainable in order to achieve a better quality of life of their citizens. However, with the rise in production, distribution and consumption, congestion problems due to the urban freight distribution can disrupt the management of the traffic that also depends on the size of the city and its population. Due to high population in urban areas, extensive commercial establishments, and the increasing demand of goods, more frequent deliveries and larger quantities of cargo shipments transiting in urban areas are needed [3]. It is a timely issue to adapt freight urban distribution to geographic, economic and cultural factors. And even though urban freight distribution has an important role in cities above 4 million habitants, the economic welfare and therefore the support of urban economies; a large number of negative effects can be shown:

Road congestion and delay: Freight movement in urban areas has a great impact on congestion even though freight vehicles typically represent between 10-15% of total traffic flow in urban areas. The Federal Highway Administration (FHWA) states that

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there has been an increase of 21% of total vehicle miles of travel (VMT) within urban areas from 1996 to 2006. Specifically, a faster growth of freight traffic in urban areas has been shown: the share of freight vehicles increased from 4.8% to 5.2%. Parking spaces and road capacity impacts also contribute negatively.

Greenhouse Gas emissions: Climate change is an important issue that needs to be addressed worldwide with devastating effects in the long term. In 2006, freight movement accounted for 9% of the total U.S. greenhouse gas emissions, and 29% of the total GHG emissions coming from transportation-related sources; and trucks emissions accounted for 68% of this total.

Air quality: While GHG emissions may not be a concern of city authorities, air quality must be. Most of all freight distribution vehicles are diesel-powered because diesel is cheaper than gas. Diesel engines directly impact on human health.

Noise pollution: big freight vehicles generate noise in urban areas during the night disturbing residents' sleep. This is a big concern for city authorities.

Safety and intimidation: Road freight vehicles, particularly big trucks intimidate pedestrians and cyclists due to their huge size. As well as the serious accidents involving big freight vehicles and cyclists or pedestrians.

In economic terms, these negative impacts could be quantified and added to the external costs associated with urban freight distribution and transportation. Due the lack of internalization by the users and operators of urban freight transportation services, not all the social costs are reflected in the price of freight transport charged by the operators to their customers. In spite of the economic benefits generated to a urban area by the urban freight transportation, there is a rational justification for intervention by the public sector and city authorities to redress the balance between social benefit and social cost derived from urban freight transportation. In this context, the concept of City logistics has come up.

The City Logistics concept came from the necessity of improving the distribution system to increase companies' competitiveness, respecting aspects as sustainability and environment. Definition of the Institute of City Logistics [4], "The process for totally optimizing the logistics and transport activities by private companies

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in urban areas while considering the traffic conditions, congestion issues and combustible consumption, with a view to reduce the number of vehicles on the cities, through the rationalization of its operations." City Logistics is also involved in all kind of freight distribution that take place in urban areas and all the activities in which it is implied and that can improve it.

Inefficiency in urban distribution can be summarized in the following ways:

- Low load factors (percentage of load used) and empty running
- A high number of low weight deliveries at a given point
- Long loading/unloading times during deliveries

All these inefficiencies in urban distribution drives to more costs for transport operators, which are passed on to receivers and customers or absorbed as costs for own account operators. However, both shippers and transport operators do not have a great incentive to increase the efficiency of their deliveries to reduce costs; because these costs represents only a small proportion of the value of the goods they work with.

Although terrestrial transportation (road) is the most polluting mode of transportation and it is responsible of huge environmental and social problems within urban areas, there is not a feasible alternative to make urban deliveries and compensate all those disadvantages. There are some key characteristics that contribute to the level of pollution in urban freight transportation:

- Old vehicles emit higher level of pollutants and GHG emissions than new vehicles; as well as higher probability of accidents, as they are more insecure.
- Since urban zones usually have narrow streets, distribution companies need to use small vehicles, because of the access difficulties to those old town areas. The use of small trucks and vans leads to more travels needed. This has an economic and environmental impact, since it is not possible to realize economies of scale.
- There are speed restrictions, traffic jams, and other conduction obligations that drivers have to deal with. Therefore, there is a stop-and-go driving pattern that leads to more fuel consumption and hence, more GHG emissions.

- Disorganized traffic and congestion problems can arise, since motorized and non-motorized vehicles share the same infrastructure. In addition, some heavy trucks are substituted by many smaller ones, because of the infrastructure and facilities, so there are more motorized vehicles.

All problems mentioned above are economical as well as societal, because these problems not only affect the efficiency and cost of transport operations, but also the air quality, environmental quality and therefore, life quality of urban areas inhabitants.

In regard to all those problems, freight distribution activity in a given urban area must deal with a lot of different challenges, including:

- Urban geography: As motorized freight vehicles utilize the road network within an urban area, geography (flat or sloping terrain) must be taken into account.
- The management of the urban traffic to avoid rush hours, congestion, and other traffic issues and taking into consideration the time of the day (peak hours).
- Parking facilities: Delivery of goods in urban centers and dense old towns is complicated since there are not many parking spots and loading/unloading zones.
- Load and vehicle size restrictions: It has been stated above that the use of many smaller vehicles to replace a few but larger ones leads to economic and environmental problems. However, it is the only alternative for the rationalization of freight movement in urban areas. Best types of vehicles, fuels, sizes should be chosen to streamline logistics operations.
- Logistics facilities and warehouses are located in the outskirts of urban areas, so traffic has been deflected to the peripheries. Therefore, it is increasingly more difficult to have access to the urban centers.
- E-commerce and other changes in commercialization lead to new forms of urban freight distribution. Logistics operators must adapt themselves to the new commercialization methods.

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All those challenges and problems drive to a dilemma. It has appeared a trade-off between the development of the logistics system and the environmental and social problems that it supposes. Changes in consumption, commercialization and hence, distribution impact to the urban environment and its limitations.

City authorities think about the environmental situation and need to find solution to traffic congestion problems and environmental externalities. Green logistics systems should be implemented in the near future, and the following criteria need to be put on practice in order to develop an effective strategy:

- Streamlining deliveries and logistics operations: traffic management is an important aspect that needs to be respected. Typical actions could be to forbid daytime deliveries in the central areas, off-peak deliveries, night deliveries with quiet motorized vehicles, and collaborative distribution of goods between different logistics operators.
- Appropriate loading and unloading zones and other freight distribution dedicated facilities to ease urban freight distribution. Urban consolidation centers, parking zones for shippers and deliveries, and collaborative warehouses are typical examples.
- The use of greener vehicles that have smaller carbon footprint, and less environmental externalities in urban freight distribution operations.
- The use of new technologies for the urban freight operations, such as GPS, other real-time information and communication software, load sharing communication systems, connected vehicles and ITS (intelligent transportation systems).

During the next few years, ITS will introduce real-time data to all actors in the supply chain. This will lead to a better understanding, control and management of the urban freight distribution systems, since information and communication between drivers, company operators and other actors will be cheap and so useful. Drivers would have information about the traffic conditions at a real-time, so they are going to be able to schedule their journey, interact with other drivers and with logistics managers.

1.3 Urban distribution problems

When it comes to schedule an urban freight distribution route, the driver has a set of delivery points he should serve, given capacity of the vehicle and time windows constraints. He should start and finish his route at the depot as well. This problem is known as the traveling salesman problem (TSP). In order to better understanding of the Transportation VRP problems, variants and applications, a brief review of the distribution problems is presented in this section.

1.3.1 The Traveling Salesman Problem

The TSP is one of the most widely famous problems in combinatorial optimization, a NP-hard problem very important in operations research and theoretical computer science. It asks the question: “Given a set of points and the distances between each pair of points, what is the shortest possible route that visits each point once and returns to the original point?” The objective is to find the shortest path through a number of customers by visiting each one only once. The problem was first formulated in 1930 and is one of the most studied problems in optimization. It is widely used as a benchmark for many optimization methods. In spite of the simplicity of the concept, the TSP is not simple regarding the computational complexity. Heuristic algorithms have been developed through years to solve the problem. The TSP is computationally difficult, but a large number of heuristics and exact methods are known, so that some cases with tens of thousands of points can be solved completely and even problems with millions of points can be approximated within a small fraction of 1% [6].

The TSP has multiple applications, such as logistics and planning. In this study, the researchers have used the TSP to calculate the number of customers that one vehicle could serve given certain time windows, as well as the VRP in the second part.

1.3.2 The Vehicle Routing Problem

The Vehicle routing problem (VRP) is a generalization of the TSP. VRP is a very well-

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known combinatorial optimization and integer programming problem. Over the past few years, the VRP has been analyzed in many research studies. This problem asks “What is the optimal set of routes for a fleet of vehicles to pass through in order to deliver a given set of customers?” In many transportation, service and distribution systems, schedule of routes of a fleet of a certain number of vehicles through a set of customers is a key issue, because of the minimization of resources. Common examples are bank deliveries, postal and parcel deliveries, garbage collection, security patrol services and the food delivery industry.

Since George Dantzig and John Ramser in 1959 [7] formulated the first VRP problem, many studies and research has been carried out and a lot of algorithms has been developed by different researchers to better solve this problem in different applications. Often, the context is that of delivering goods located at a central depot to customers who have placed orders for such goods. The objective of the VRP is to minimize the total route cost. In 1964, Clarke and Wright [8] improved on Dantzig and Ramser's [7] approach using an effective greedy approach called the savings algorithm.

Determining the optimal solution is an NP-hard [9] problem in combinatorial optimization, so the size of problems that can be solved optimally is limited. The commercial solvers therefore tend to use heuristics due to the size of real world VRPs and the frequency that they may have to be solved.

The VRP concerns the service of a pickup or delivery company. How things are delivered from one or more depots which has a given set of vehicles operated by a set of drivers who can move on a given road network to a set of customers. It asks for a determination of a set of routes (one route for each vehicle that must start and finish at its own depot), such that all customers’ requirements and constraints are satisfied and the total transportation cost is minimized. This cost may be monetary, distance, environmental or otherwise. The road network can be described using a graph where the arcs are roads and vertices are junctions between them. The arcs may be directed or undirected due to the possible presence of one way streets or different costs in each direction. Each arc has an associated cost which is generally its length or travel time which may be dependent on vehicle type. [8]

To know the global cost of each route, the travel cost and the travel time between each customer and the depot must be known. To do this our original graph is transformed into one where the vertices are the customers and depot and the arcs are the roads between them. Sometimes it is impossible to satisfy all of a customer's demands and in such cases solvers may reduce some customers' demands or leave some customers unserved. To deal with these situations a priority variable for each customer can be introduced or associated penalties for the partial or lack of service for each customer given.

The objective function of a VRP can be very different depending on the particular application of the result but a few of the more common objectives are:

- Minimize the global transportation cost based on the global distance travelled as well as the fixed costs associated with the used vehicles and drivers
- Minimize the number of vehicles needed to serve all customers
- Least variation in travel time and vehicle load
- Minimize penalties for low quality service
- Minimize the environmental impact

Several variations and specializations of the vehicle routing problem exist:

- Vehicle Routing Problem with Pickup and Delivery (VRPPD): A number of goods need to be moved from certain pickup locations to other delivery locations. The goal is to find optimal routes for a fleet of vehicles to visit the pickup and drop-off locations.
- Vehicle Routing Problem with LIFO: Similar to the VRPPD, except an additional restriction is placed on the loading of the vehicles: at any delivery location, the item being delivered must be the item most recently picked up. This scheme reduces the loading and unloading times at delivery locations because there is no need to temporarily unload items other than the ones that should be dropped off.
- Vehicle Routing Problem with Time Windows (VRPTW): The delivery

locations have time windows within which the deliveries (or visits) must be made.

- Capacitated Vehicle Routing Problem: CVRP or CVRPTW. The vehicles have limited carrying capacity of the goods that must be delivered.
- Vehicle Routing Problem with Multiple Trips (VRPMT): The vehicles can do more than one route.
- Open Vehicle Routing Problem (OVRP): Vehicles are not required to return to the depot.

The transportation decisions associated with high value–high time sensitive products are the most demanding activities in terms of transport service requirements and usually require service within a hard time window [10]. Time windows are a key constraint also for make to order-JIT production systems as well as emergency repair work and express (courier) delivery services. Time windows have a significant impact on decreasing the efficiency of routes, reducing service areas, and significantly increasing distance travelled [11].

A seminal contribution to the estimation of the length of a shortest closed path or tour through a set of points was established by Bearwood et al. [12]. These authors demonstrated that for a set of n points distributed in an area A, the length of the TSP tour through the whole set asymptotically converges, with a probability of one, to the product of a constant k by the square root of the number of points and the area, i.e. k √nA when n tends to infinity. The asymptotic validity of this formula for TSP problems was experimentally tested by Ong and Huang [13] using nearest neighbor and exchange improvement heuristics. Eilon et al. [14] proposed several approximations to the length of CVRP based on the shape and area of delivery, the average distance between customers and the depot, the capacity of the vehicle in terms of the number of customers that can be served per vehicle, and the area of a rectangular delivery region. Daganzo [15] [16] proposed a simple and intuitive formula for the CVRP length when the depot is not necessarily located in the area that contains the customers.

$$CVRP(n) \approx 2rn/Q + 0.57\sqrt{nA}$$

In this expression CVRP (n) is the total distance of the CVRP problem serving n customers, the average distance between the customers and the depot is r, and the maximum number of customers that can be served per vehicle is Q. Hence, the number of routes m is a priori known and can be calculated as n/Q. Daganzo's approximation can be interpreted as having: (a) a term related to the distance between the depot and customers, and (b) a term related to the distance between customers. The coefficients of Daganzo's approximation were derived assuming $Q > 6$ and $n > 4Q^2$. Daganzo's approximation works better in elongated areas as the routes were formed following the ''strip'' strategy.

Although Daganzo's formulas are useful and intuitive they are not easily applied to estimate VRP distance since his approach does not guarantee feasibility. Unfortunately, no systematic method or general expression for clustering and determining the number of periods that guarantees balanced periods and feasible routes is provided. Approximations to the average length of vehicle routing problems have recently been contributed by Figliozzi [17] to estimate VRP distance when the number of customers served (n) and the number of routes (m) are given. The formula proposed accounts for the tradeoffs between connecting distance and local tour distance as the number of routes increases:

$$VRP = k_1 \frac{n-m}{n} \sqrt{nA} + 2\bar{r}m$$

The parameter k_l is estimated by linear regression; the value of kl is a function of the spatial distribution of customers. The term (n-m)/n is shown to improve MAPE values in problems with capacity constraints, time windows constraints, and a varying number of customers served (n).

Tipagornwong and Figliozzi [18] modified the approximation model to incorporate specific characteristics of tricycles. In this study, we use that model to minimize the total emissions produced by tricycles and diesel vans along their life cycle.

1.4 Project aims and scope

As has been stated before, the minimization of the use of resources is a common motivation in all logistics fields. In this study, we focus on minimize lifecycle emissions. In order to minimize greenhouse gas emissions along the vehicles lifecycle, Tipagornwong and Figliozzi [18] model is applied to minimize the number of vehicles and distance traveled; because both distance and number of vehicles can be converted to greenhouse gas emissions.

Unlike previous research efforts, the model presented in this research include all stages in vehicle production and recycling and also incorporates logistics restrictions (delivery time, cargo, customer distribution) and parking characteristics of tricycles and vans. In addition, due to the small size and payload of electric tricycles, more than one tricycle can be replaced by a diesel delivery van. Hence, it is necessary to estimate what is the number of vans that minimizes lifecycle emissions for this vehicle type.

The model presented in this section was utilized to estimate the number of vans that minimizes lifecycle emissions while satisfying all the logistics constrains that B-line vehicles must meet. The lifecycle emissions model is presented below in the methodology section. Next section provides a brief introduction to transportation GHG emissions, and why it is an interesting and timely topic in the transportation research.

1.5 Transportation GHG emissions

Our Earth is warming. Earth's average temperature has risen by 1.5°F over the past hundred years, according to the Environmental Protection Agency [19], and it is projected to soar between 2 and 11.5°F over this century. According to scientist, human influence on the climate system is clear, emissions of Greenhouse gas (GHG) are the highest in history and this can translate to catastrophic consequences.

The most important GHGs are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), but the most common is CO_2, which accounts for 82% of U.S. Total Greenhouse Gas Emissions in 2013. During most of the past 800,000 years, CO_2 fluctuated between about 180 parts per million (ppm) during iced ages and 280 ppm during interglacial warm periods. Human activities since the Industrial Revolution have produced a 40% increase in the atmospheric concentration of CO_2 as high as 400 ppm

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in April 2014 [19]. This levels of CO_2 have not been that high since the Pliocene Epoch, which was between 3 and 5 million years ago, according to the Scripps Institution of Oceanography [20]. If greenhouse gas emissions continue at the present rate, Earth's surface temperature could exceed historical values as early as 2047, with disastrous effects on ecosystems, biodiversity and the livelihoods of people worldwide.

Greenhouse gas emissions from transportation accounted for 27% of total U.S.A. GHG emissions in 2013, and have risen by 16% since 1990 [19]. The Intergovernmental Panel on Climate Change (IPCC) reported on 2014 [21], on the Fifth Assessment Report (AR5), a growth in GHG emissions has continued since the previous report (AR4, 2007) although more efficient vehicles and policies being adopted. Vehicles are now more efficient, but transportation emissions are still growing in an unacceptable rate. Reducing global transport GHG emissions will be challenging because transport emissions are strongly coupled with GDP growth. The continuing growth in passenger and freight activity will outweigh all mitigation measures unless a radical change to electric vehicles and renewable electricity sources can be made.

Since 2008, truck vehicle miles traveled (VMT) in the U.S. had been increasing as a result of economic growth, more international trade, and more intercity trade [22]. Truck traffic makes up about 10% of VMT on urban Interstates and 7% on other urban road-ways, with higher shares in the denser core, where automobiles constitute a smaller share of passenger traffic. In 2006, freight movement accounted for 9% of the total U.S. greenhouse gas emissions, and 29% of the total GHG emissions coming from transportation-related sources; and trucks emissions accounted for 68% of this total [23]. Trucking emissions are caused by VMTs but also by idling. Idling is ubiquitous at ports and intermodal stations as well as inner city streets as a result of traffic congestion and during deliveries. According to Cambridge Systematics [24], idling trucks only in the U.S. consume about 20 million barrels of diesel fuel and generate 10 million tons of CO_2 annually.

Traffic congestion has a great impact on fuel efficiency and CO_2 emissions because of the relationship between vehicle operating speed and the rate of CO_2 per mile traveled. According to Figliozzi [25], there is a rapid non-lineal growth in emissions and fuel consumption as travel speed fall below 30 mph, as high as double on

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a per mile basis when speed drops from 30 to 12.5 mph, as well as when speed drops from 12.5 to 5 mph. Congestion affect emission rates because fuel consumption is a function of both acceleration rates and travel speeds. Consequently, stop-and-go traffic conditions and frequent changes in speed increases emission rates.

Several empirical studies confirmed that urban freight vehicles account for 6-18% of total urban travel [26] [27]. Furthermore, 21% of CO2 emissions come from urban freight vehicles [27] [28]. Taking into account that the transportation sector is responsible for 29% of total greenhouse gas (GHG) emissions in the United States, the contribution of the urban freight transportation is extremely relevant. In addition, urban freight vehicles (commonly diesel) are known to seriously affect health of citizens. Diesel motor vehicles are a major source of air contaminants produced during the diesel combustion, like Mono-nitrogen oxides (NOx), which react to form smog and acid rain [29]. There are other criteria air contaminants that damage our ecosystems and increase health risks to residents [30], including sulfur oxides (SOx), carbon monoxide (CO) and particulate matter (PM). Consequently, governments are seeking to mitigate these problems by cutting GHG emissions and other air pollutants.

Urban freight management efforts have environmental mitigation as a primary objective, and one environmental strategy is switch to alternative fuels and vehicles. Environmental advocates, policy-makers and the trucking industry have great expectations for use of electric commercial vehicles in urban freight movement. Emissions reductions are expected to be high, because of the stop-and-go patterns of urban delivery operations or also called "last mile" transport.

Summarizing, as it is very well known, cities roadway capacity and parking space are limited. Considering that passengers and freight transport compete for this space, trends in logistics (higher frequency of deliveries and smaller order size because of just-in-time systems) are now increasing negative transport externalities like traffic congestion, poor level of road safety, crashes and accidents, energy wastefulness, air and noise pollution, and more miles traveled.

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2. Electric vehicles literature review

2.1 Electric vehicles in urban distribution schemes

One possible strategy to tackle the negative effects of urban freight is the electrification of urban delivery vehicles [31]. In congested urban areas, delivery trucks have low fuel economy because they spend a great portion of their time idling [32]. In addition, electric motors provide higher efficiency than internal combustion engines in a urban environment in which average driving speed is low [33]. Another advantage is that systematic recharging or battery swapping are feasible because these delivery vehicles make similar routes every day and after each route return to the company garage [34]. Hence, the switch from a fossil fuel combustion fleet to an electric-powered fleet seems like a suitable solution to reduce urban emissions. One of the great advantages of vehicles electrification is that it would couple the transportation and the electric sectors and shift emissions from the vehicles in urban areas to the power stations, improving cities' air quality.

A strategy to reduce transportation emissions is switch to vehicles with a smaller carbon footprint. Environmental advocates, policy-makers and the trucking industry have great expectations for use of electric commercial vehicles in urban freight movement. Emissions reductions are expected to be high, especially in areas with low speed, high congestion, and high idling rates during deliveries and the last mile of transportation.

Experimentation with respect to last mile issues is far more extensive in Europe than inside the United States, due to higher density urban cores, narrow streets and less road capacity, older building stock and hence limited loading and parking facilities.

One of the environmental strategies to reduce urban truck traffic is the "City logistics" and consolidation schemes, which seek to remove freight vehicles by finding ways to combine the pick-ups and deliveries of different shippers and different receivers. The focus is on changing the last mile of the supply chain. On this context, urban

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consolidation centers and companies which provide last mile logistics by using electric vehicles have been increasingly appearing in European cities. Specifically, electrically powered cargo cycles have progressively emerged in the most densely populated city centers.

Another strategy to reduce urban truck traffic is the utilization of urban consolidation centers which seek to remove freight vehicles by finding ways to combine the pick-ups and deliveries of different shippers and different receivers (Dablanc et al., 2013 [35]). Urban consolidation centers and companies which provide last mile logistics by using electric vehicles and/or tricycles have been increasingly appearing in European cities (Schiliwa et al. 2015 [36]).

A study documents the benefits of the Chronopost Concorde urban consolidation center located in downtown Paris (TURBLOG, 2011 [37]). Chronopost is a big French express parcel company and the Chronopost Concorde facility is an urban depot where deliveries are first trucked and later moved to electric vehicles for last-mile delivery; a fleet of 16 electric vehicles is utilized for final deliveries to clients. Chronopost achieved higher productivity, 70 deliveries per route instead of 56, and CO2 emissions decreased by 60% in a six-month period. One-third of the decrease was due to the new logistics organization and two-thirds of the reduction was due to the use of an electric van fleet for final deliveries. Browne et al [38] evaluated a trial in which office supply was delivered from a suburban London depot to final customers in downtown. During the trial diesel vans were replaced by electric vans and tricycles operated from a consolidation center close to downtown. Deliveries are first trucked and later moved to electric vehicles for last-mile delivery in downtown London. A total of six tricycles and three electric vans delivered the cargo from the distribution center to final customers. The operation of these electric vehicles did not result in any fossil fuel consumption or GHG emissions because the electricity used by these electric vehicles was produced from renewable sources. The result showed great benefits; total distance travelled was reduced by 20% and the CO2e emissions per parcel fell by 54%. GNewt Cargo was the operator of the micro-consolidation center, tricycles, and electric vans.

2.2 Electric vehicles literature review

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In particular, electrically-assisted cargo tricycles could play a role in reducing GHG emissions from the freight transportation sector. Cargo tricycles are ideal low-emission alternative to transport light goods in city centers not only because their lack of tailpipe emissions, but also because their small size and easy access to compact, congested towns and cities. Unlike conventional diesel-powered vans, cargo tricycles can legally use bicycle paths and lanes allowing for faster access to congested downtown or pedestrian areas [39]. Cargo tricycles operations are not significantly affected by congestion or lack of loading/unloading parking areas. Other advantages are noise reduction through the use of quieter vehicles, improved safety for pedestrians and less conflicts in traffic with passenger cars and other road users in general [39].

Although past and current research efforts into cargo tricycles benefits are extensive, most research efforts have ignored vehicle production and disposal emissions when evaluating environmental impacts. To the best of the authors' knowledge, there is no published carbon footprint assessment of a tricycle logistics company in the existing literature.

Here we explore the greenhouse gas (GHG) emissions saving potential of electric urban delivery tricycles over their life time for urban delivery operations. B-Line [40] is a tricycle logistics company that is currently providing warehousing, pick-up, and delivery services in downtown Portland, OR. The researchers were able to record and analyze several days of detailed B-Line GPS route and warehouse data. The goal is to compare B-Line's carbon footprint against the footprint of traditional pick-up and delivery companies. Because the freight that is delivered by tricycle is often light and small, diesel vans are the natural competitor.

Smaller vehicles (tricycles) have a smaller production and disposal carbon footprint (USDOE, 2015 [41]) but the tradeoffs are not so clear when several smaller vehicles can be replaced by a larger vehicle (e.g. diesel vans).

Although electric tricycles do not produce tailpipe emissions, greenhouse gas (GHG) emissions from electricity generation are substantial. And even though electric tricycles may have greater tank-to-wheel (TTW) efficiency than conventional diesel-powered vans in city delivery operations, the overall energy efficiency of electric tricycles depends on life-cycle energy use including upstream electricity generation and

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transmission efficiency. An assessment of tricycle and diesel van life cycle emissions is carried out, ranging from extraction of raw materials from the earth to vehicle manufacturing, use stage, and recycling/disposal at the end. For the use phase, B-Line operations are analyzed to study how that delivery services could be provided by more traditional diesel powered fleets.

In order to understand the topic of tricycle logistics service, it is essential to break down and analyze the characteristics of cargo tricycles, and also to quantify their environmental effect in the role they play as last-mile vehicles in urban distribution.

2.2.1 Characteristics of Cargo Tricycles

Cargo tricycles are often electric-assisted. La Petite Reine and Cycles Maximus are two important manufacturers of cargo tricycles. On a regular basis, the tricycle payloads are within 331lbs and 600 lbs, and their maximum speed is approximately 10 mph [42]. Differences between cargo tricycles and diesel vans can be identified in Table 1, where vehicles specifications of a typical cargo tricycle and van are shown.

TABLE 1 Specifications of Typical Diesel Van and Tricycle

	Electric tricycle	**Diesel cargo van**
Specification	**Cycles Maximus**	**GMC Savana 2500**
Price	6,200 dollars [a]	41,500 dollars [b]
Battery size / Tank size	864 watt – hour [a]	31 gallons [b]
Battery capacity	72 - 92 Ah [a, c]	-
Gross Vehicle Weight Rate	1,100 lbs [d]	8,600 lbs [b]
Curb Weight	500 lbs [d]	6,118 lbs [b]
Battery Weight	77.8 lbs [c]	-
Max Payload	600 lbs [d]	2,482 lbs [b]
Cargo Volume	60 ft3 [d]	239.7 ft3 [b]
Range	30 miles [a]	465 miles [e]
Max Speed	10 mph [f]	50 mph [h]
Fuel economy (city)	25 – 50 watt-hour/mile [d]	15 mpg [g]

[a] Cycles Maximus [18]
[b] GMC Vans Savana Cargo [19]
[c] Odyssey Batteries [20]
[d] Provided by B-Line [16]
[e] Based on the fuel economy.
[f] Conway et al. [17]
[h] Typical urban area maximum speed.
[g] 2014 Vehicle Technologies Market Report, US Department of Energy [21]

Cargo tricycles have many advantages. Because their small size, tricycles require minimal parking space and can be parked legally on- and off-street, on sidewalks or inside business [18]. A diesel van would need to park-on-street, increasing the walking time and distance to make a delivery, and commonly requiring the vehicle to idle while waiting for parking. The driver of a delivery van has either to cruise for a free parking space or double-park illegally, and this increase cost, emissions, and traffic congestion. Using tricycles, customer service times can be reduced.

In terms of maneuvering throughout urban areas, tricycles also tend to have a distinct advantage, because there are dedicated bicycle lanes a tricycle can use to bypass traffic congestion at all times. Furthermore, the possibility of simplifying and shortening the route by crossing pedestrian areas or riding up one-way streets on a sidewalk in the opposite direction makes a tricycle the perfect vehicle to deliver in dense downtowns. Lastly, a tricycle has better fuel economy in terms of energy, because of its lower weight and because riders have to pedal.

Wilson et al. [43] state that an average fit man or woman could pedal a bicycle with the power output of 75 watts without suffering fatigue for 7 hours. The human contribution is not insignificant, because power exerted by the rider could reduce necessary battery size by around 500 watt-hours during a 7-h day, and battery capacity is around 850 watt-hours.

Although there are many advantages to cargo tricycles, there are also several disadvantages. Since tricycles have limited payloads and volume capacities, there are times where freight is not deliverable due to it exceeding the vehicles limit, both in weight or volume. Limited travel range and low speed in free-flow conditions are also crucial disadvantages. Therefore, tricycles only fit as an urban delivery vehicle in certain contexts, that is, small volumes and low weight parcels when a diesel van delivery process is constrained by the limitations of the urban structure.

2.2.2 Decarbonizing the last-mile

Urban mobility accounts for 40% of all CO2 emissions of road transport and up to 70% of other pollutants from transport (European Commission, 2015). Urban congestion is not only causing an increase in environmental pollution and energy consumption, but also increases the length of private and commercial journeys. Every year the European economy loses around 1% of GDP due to congestion (European Commission, 2011). Public health is affected by these facts since traffic emissions are responsible for 70% of the cancerous and other dangerous substances (Silva & Ribero, 2009).

Cargo tricycles are mostly used in the 'last mile' of the logistics chain, defined as the distribution of goods from an urban distribution center to final customers. Cargo cycles are a zero emission alternative to light goods vehicles in city centers.

A systematic literature review has been performed to find relevant literature within the field of sustainable urban freight transport addressing the use of cargo bikes, bicycles and cargo tricycles by searching within academic databases Science Direct (www.sciencedirect.com) and Google Scholar (www.scholar.google.es) To date, the existing research efforts into the use of cargo tricycles within urban 'last mile' logistics are still scattered [36] [48] [49]. Most of the studies are limited to the European context, since cargo tricycle delivery is better suited to the narrow streets of the old town. Popular examples are located in Brussels, London and Paris [42] [50].

ºStudies are mostly limited to the European context, and most research effort has been focused on identifying the market niche within logistics sector [36]. Specific case studies of either cities or companies. In terms environmental effects, the body of research is relative scarce. However, there are some studies and some companies which have put across emissions savings data. For instance, GNewt Cargo [51], a green delivery company in London, has been independently verified to cut CO2 emissions per parcel delivered by 62%, according to their website. Ecopostale [52], a Belgium company, estimates 29 tons of CO2e savings, comparing their delivery service against a traditional delivery company; and Txita [53], a tricycle delivery company of San Sebastian (Spain) estimates the saving in CO2e, compared with the use of commercial vans, at 14 tons, based on 59,247 parcels delivered in two years. A Dutch study [54] estimated possible annual savings for the Netherlands of 21,000 tons of CO2.

Browne et al. [38] evaluated a trial in which office supply was delivered from a suburban London depot to final customers in downtown. During the trial diesel vans were replaced by small electric vans and tricycles operated from a Micro-Consolidation Center close to downtown. A truck journey was needed to transport cargo from suburban London to the distribution center in downtown London. Then, 6 tricycles and 3 electric vans delivered the cargo from the distribution center to final customers. The operation of these electric vehicles did not result in any fossil fuel consumption or greenhouse gas emissions because the electricity used by these electric vehicles was produced from renewable sources. The result showed great benefits: total distance travelled was reduced by 20% and the CO2e emissions per parcel fell by 54%. GNewt Cargo [51], was the operator of the micro-consolidation center, tricycles and electric vans.

Conway et al. [42] analyzed two tricycle delivery services in New York City. Emissions reductions were estimated assuming that Cycles Maximus cargo tricycles replaced daily operation of five-year-old cargo van. The annual savings were between 19 and 21 tons of CO2, and between 3.4 and 4 lbs. of PM10 due to cargo tricycles operations in NYC. Because the Cycles Maximus vehicles in use by the case study operators were fully human-powered, no emissions are released during their operation and therefore emissions savings were evaluated by estimating emissions rates for the comparative motorized urban delivery vehicles using the EPA's MOVES model [55].

Unlike previous research efforts, this research analyzes all lifecycle stages of tricycles and vans and also utilizes a highly detailed dataset obtained from shadowing real-world operations of a tricycle logistics company. In addition, a logistic model based on continuous approximations is created and emissions elasticity values are estimated and analyzed.

Overall, most of studies found that the use of cargo cycles is a viable solution for urban freight transport. Lenz and Riehle (2013) suggest that cycle freight can form around 25% of city centre commercial traffic in the medium term and that a potential market does exist. A recent outcome of the project Cyclelogistics (www.cyclelogistics.eu) performed in Europe indicates a higher potential, stating that in average 51% of all motorized trips in European cities that involve transportation of goods could be shifted to bikes or cargo cycles.

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3. Portland Case Study. B-Line

A case study was conducted using real-world data from Portland, OR to investigate the GHG emissions savings. This was done through the use a tricycle logistics service. Portland is known as one of the most bike-friendly cities in US. There are many bike paths throughout the city, which makes biking convenient. In addition, the Portland downtown area is flat. That being the case, companies like B-Line are able to exist.

B-Line Sustainable Urban Delivery [40] was founded in February of 2009. The company delivers a wide variety of products, such as produce, baked goods, coffee beans, bike parts, and office supplies to restaurants, coffeehouses, bike shops and office buildings. B-line also performs reverse logistic services with the pickup and consolidation of materials for recycling. B-Line only utilizes electric and human powered cargo tricycles for delivery and pickups. Most of the B-Line customers are located in or nearby Portland downtown area. B-Line distribution warehouse is located only 2 miles from downtown Portland as shown in Figure 1.

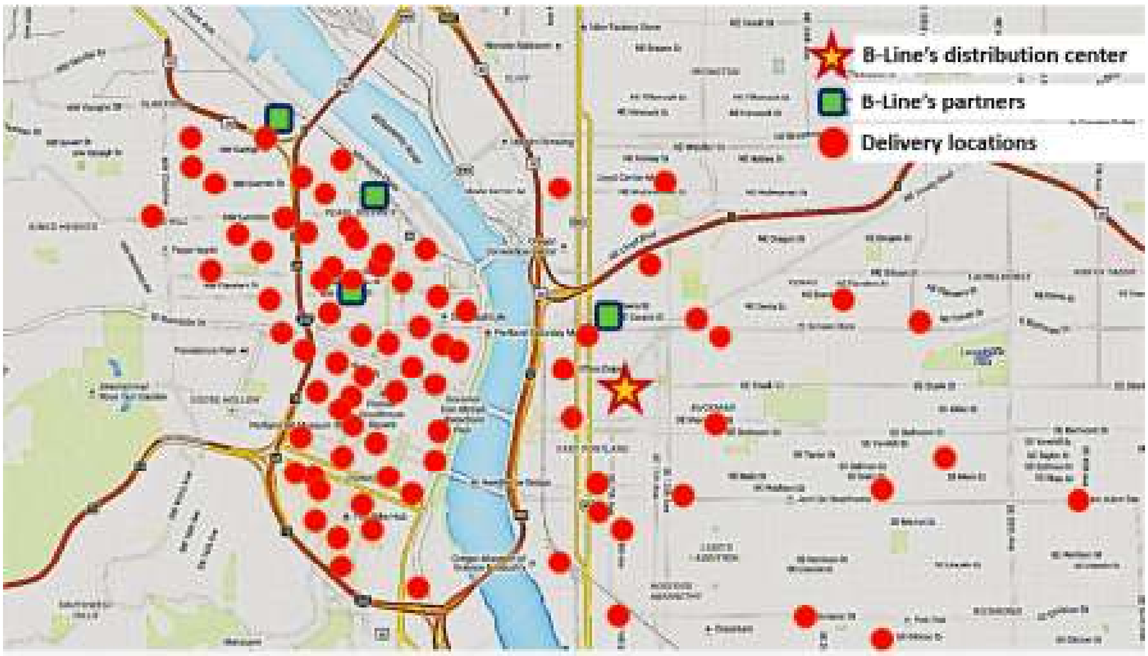

FIGURE 1. B-Line distribution warehouse, partners and customers location in

downtown Portland.

B-Line depot is located near the edge of downtown and can be considered as an urban consolidation and distribution center. B-Line routes are complex because tricycles volume optimization is essential to achieve competitiveness. It involves traditional distribution from the depot with time windows but also intermediate pick-up at other partners' and customers' locations and delivery of those goods. In addition, the backhaul is in many cases utilized to consolidate (bring back to the B-Line depot) waste material for recycling. As many other urban delivery companies, B-Line provides both forward and reverse logistics services. Routes may include both pickup(s) and deliveries.

B-Line's partners transport their products from their respective warehouses to B-Line's depot and then B-Line delivers those products by tricycle. B-line currently operates seven days per week and provides delivery services for eight companies. Two of its major partners transport their products from their respective warehouses to B-Line's distribution center every morning between 6am and 9am. Two other companies transport goods once a week. The remaining four partners are located in or close to downtown, thus B-Line picks-up products of their locations and distribute to final customers.

This research only considers the distribution of goods delivered from B-Line's depot to customers, approximately 90% of the products delivered. For the sake of brevity and to facilitate the comparison of the results with previous research efforts, this research does not analyze the benefits and/or GHG emissions reductions of reverse logistic services for the pickup and consolidation of materials for recycling.

On May 2015, the researchers were able to collect detailed route and warehouse/depot operations data. Detailed vehicle and batteries data was provided by the full-time mechanic at the depot. Partners operations and warehousing consolidation data was provided by the operations manager. Several days of detailed GPS route data was recorded utilizing a smartphone application called ORcycle (http://www.pdx.edu/transportation-lab/orcycle). The GPS data was then mapped and

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analyzed to estimate route durations, tricycle speeds, and customer service times. Table 1 presents a summary of some key average values that describe the scope of B-Line operations.

Characteristic or Parameter	**B-Line delivery system**
Number of daily deliveries	80
Delivery area size (mi2)	8 sq. miles
Distance from warehouse (mi)	2 miles
Customer demand (lb.)	65 lbs.
Working hours (h)	8 hours
Total distance traveled per day	82 miles
Customer service time (min)	10 minutes
Delivery days per year	360 days

TABLE 2. Delivery service characteristics and planning parameters.

B-Line owns 6 tricycles made by Cycles Maximus and 12 Lead Acid AMG batteries made by Odyssey Battery. Two batteries are needed for each tricycle; one for the morning route and one for an afternoon route. Batteries are swapped after a route to ensure that batteries do not reach a low state-of-charge which may result in reduced battery life. During several years B-Line staff has collected 1,150 observations related battery energy parameters before and after each route. Utilizing this data, we estimated a median fuel economy of 48.65 watt-hour/mile (20.55 miles/kWh). Since these measurements were taken from the batteries themselves (not from the electric motor), electricity losses as a result of batteries energy transmission inefficiency are included in this median number. In addition, chargers and power converters connected to the grid are drain small amounts of power and there are some efficiency losses when the battery is charging; an efficiency level of 85% is typical in the literature (Stevens and Corey, 1996). In this study, we assume an average charging efficiency level of 70% in order to avoid over-estimating tricycle's fuel efficiency. Battery chargers life-cycle impacts (materials, production, assembly and recycling) are excluded from this assessment, because of their small number, low weight and long life expectancy.

The goal of this research is to compare lifecycle GHG emissions of tricycles and

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conventional diesel vans. The specifications of a typical cargo tricycle and the assumed values for a diesel van are shown in Table 2.

Specification	Electric tricycle Cycles Maximus	Diesel cargo van RAM ProMaster 2500
Gross Vehicle Weight Rate	1,100 lbs.	8,941 lbs.
Curb Weight	500 lbs.	4,781 lbs.
Battery Weight	77.8 lbs.	-
Engine Capacity	-	3.6 liter V-6
$e_{vehicle\ material}$	4.108 lbs CO2e / lbs vehicle	3.995 lbs CO2e / lbs vehicle
$e_{assembly+disposal+recycling}$	1.247 lbs CO2e / lbs vehicle	1.247 lbs CO2e / lbs vehicle
$e_{battery}$	3.93 lbs CO2e / lbs battery	-
$e_{well-to-tank}$	0.846 lbs CO2e / kWh	5.108 lbs CO2e / gallon
$e_{tank-to-wheel}$	-	22.72 lbs CO2e / gallon
Charger efficiency	0.7	-
Max Payload	600 lbs.	4,160 lbs.
Range	30 miles	465 miles
Fuel economy (city)	48.65 watt-hour/mile	18 mpg
Fuel economy (find a parking)	-	8 mpg
Idle fuel consumption	-	0.57 gallon / hour
Life time (years)	5 years	12 years
Distance to find parking (ft.)	0 ft.	200 ft.
Time to find parking (min)	0 min	3 min
Average speed inside service area	7 mph	10 mph
Average speed outside service area	7 mph	30 mph

TABLE 3. Vehicle characteristics and emissions parameters.

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4. METHODOLOGY

A Carbon footprint (greenhouse gas emissions assessment) quantifies the total emissions that contribute to global warming caused by an organization or project [33]. The assessment quantify GHG emissions of carbon dioxide, methane and mono-nitrogen oxides and then converts these emissions into carbon dioxide equivalents (CO2e), typically with a time horizon of 100 years using the global warming potential values recommended by the Intergovernmental Panel on Climate Change [34].

The GHG Protocol is the "most widely used international accounting tool for government and business leaders to understand, quantify, and manage greenhouse gas emissions", according to the GHG Protocol website [35]. The GHG Protocol defines direct and indirect emissions differentiating whether they are emissions from sources that are controlled by the company studied, or they are consequence of the company studied but occur at sources controlled by other organizations. Three broad scopes are also defined: [I] All direct GHG emissions. [II] Indirect GHG emissions from consumption of purchased heat or electricity; and [III] Other indirect emissions, such as the extraction and production of purchased materials and fuels, transport operations in vehicles not controlled by the organization, electricity-related activities (e.g. transmission and distribution losses), outsourced activities, etc.

This study includes GHG emissions associated with energy use and fuel consumption, along with vehicle and battery production, use and disposal, in an attempt to estimate the most comprehensive possible Carbon Footprint assessment.

In that context, Life cycle assessment (LCA) of systems should be introduced. LCA (also known as a 'cradle-to-grave' assessment) assess multiple environmental impact categories, which may include global warming of GHG emissions, but may also include human health impacts, ecosystem and resources impacts, land use, etc. While Carbon Footprint separates out the inputs into three scopes, LCA commonly separates the inputs into life cycle phase (ranging from extraction of raw materials from the earth, to process of those materials, manufacturing, distribution, product use, and

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recycling/disposal at the end). Life cycle stages should be analyzed from the perspective that each stage depends on the one before it. LCA helps to avoid shifting environmental problems from one place to another, by considering the entire life cycle system.

In this paper, we compare the Carbon Footprint of a tricycle logistics company against the footprint traditional pick-up and delivery companies covering the broadest GHG Protocol scope; that is, including all life cycle emissions associated with the production, use and disposal of vehicles. The two commercial vehicles are as follows: a conventional internal-combustion (IC) diesel-powered cargo van such as the GMC Savana 2500 and an electric-powered cargo tricycle such as the Cycles Maximus cargo trike. Vehicle specifications are shown in Table 1.

We examine commercial vans and electric tricycles in three distinct phases: (a) vehicle cycle, from raw material extraction to disposal but without considering vehicle utilization; (b) well-to-tank or the lifecycle of fuel/electricity production and distribution; and (c) tank-to-wheel or vehicle use operation. Next section focuses on the vehicle cycle assessment (a) that does not include vehicle utilization. The present comparative of life cycle emissions between diesel and electric tricycles is conducted using LCA tools and real-time data. To execute a LCA, several software tools are available. For transportation analyses in particular, GREET [36] is a widely known option. Other data used in this study is collected from publicly available sources such the U.S. Environmental Protection Agency [37] and, the eGRID database [38].

4.1 Life-cycle assessment of vehicles

Vehicle production and disposal includes several stages: extraction of raw materials (including aluminum, iron, plastic, copper), transport to factories where alloys are developed, refinement of raw materials and production of final materials, transportation of these materials to assembly plants, production of vehicles at the vehicle assembly factories, transport and distribution of vehicles to dealers and then, after the use phase, disposal or recycling of vehicles. GHG emissions of these stages are estimated using the GREET model which uses vehicle weight as the functional unit (USDOE, 2015). The GREET model contains hundreds of parameters with default values based on

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national/regional statics or industrial practice. Detailed documentation of assumptions in relation to industrial processes and technologies are available on GREET publications (USDOE, 2015).

To estimate GHG emissions from vehicle manufacturing (not including the tricycle battery), we use the GREET 2014 model [36]. The GREET model does not include the e-tricycle vehicle type, hence, the electric tricycle was modeled as an electric vehicle pick-up truck with conventional materials. The conventional diesel van was modeled as a pick-up truck with an internal combustion engine and conventional materials. Vehicles weight and vehicle production, materials and disposal emissions rates are shown in Table 1. Detailed environmental impacts are provided for numerous materials and manufacturing processes, the GREET model breaks down different vehicle technologies into their constituent systems, components and parts considering mass and material composition. Those breakdowns are obtained from a large number of reports (44, 45).

The functional unit selected is mass (lbs.) of each vehicle, both for raw material recovery, processing and fabrication, and for vehicle component production, assembly and disposal/recycling. The material composition of each vehicle type is estimated with the GREET vehicle cycle by using real weights shown in Table 1. In our approach we consider an electric cargo tricycle as a pick-up truck (EV conventional material) and a commercial diesel van as a pick-up truck (ICEV conventional material). Vehicle life cycle GHG emissions are 2,677 lbs. of CO2e for a Cycles Maximus cargo tricycle and 32,073 lbs. of CO2e for a GMC Vans Savana Cargo diesel van.

4.2 Battery life cycle

Electric-tricycles typically use Lead-Acid (PbA) batteries. Although Lead-acid is the oldest type of rechargeable battery, is still attractive due to their low cost and high specific power. Valve-regulated lead-acid (VRLA) do not require constant maintenance, unlike the initial “flooded” design. AGM dominates the VRLA market share, due its extremely high Energy/Weight density and excellent overall performance.

Sullivan and Gaines [39] conducted a full process-based life-cycle analysis (LCA) of

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VRLA battery. In comparison with other battery technologies, the PbA battery has the lowest cradle-to-gate (CTG) emissions footprint, because of its highly successful recycling processes and infrastructure [40]. Currently, new PbA batteries range from 60% to 80% recycle content (Battery Council International 2010). Rantik [41] analyzed the recycling processes of PbA battery. The emissions associated to batteries recycling or disposal stage was taken from Rantik (1999). Combining these sources and using the GWP values recommended by the International Panel on Climate Change to convert CH4 and N2O, it is estimated that battery life cycle GHG emissions are 3.93 kgCO2e/kg of PbA battery. Battery weight and emissions rate are shown in Table 1.

4.3 Use phase

The majority of life cycle GHG emissions are emitted during the use phase. In this carbon footprint comparison between electric-tricycles and commercial vans, emissions from vehicle maintenance are omitted assuming to be similar or that the difference is minimal in comparison with other life cycle phases.

4.3.1 Well-to-Tank: emissions of energy supply chain.

This is the well-to-tank (WTT) analysis of emissions that includes all the emissions in the energy supply chain. The diesel and the electricity supply chains are analyzed individually.

Diesel fuel supply chain

Life cycle GHG emissions for a typical fuel such as diesel include several stages: from petroleum pumping, extracting, transporting, refining in factories, dispensing and distributing through to diesel stations.

Next to the use phase, the diesel supply chain is the most polluting stage on the life cycle of a vehicle [42]. It has been estimated that around 20% of the life-cycle GHG emissions of fossil fuels like petrol and diesel are emitted during extraction, transport and refining processes [43]. Using the GREET model and gallons U.S. average mix of diesel as the functional unit, the diesel GHG emission factor is estimated and shown in Table 2. These upstream GHG emissions were estimated to be about 5.108 lbs. of CO2e per gallon of conventional diesel US refineries average.

Electricity supply chain

Although electric tricycles do not produce direct emissions, greenhouse gas emissions from electricity generation may be substantial. Electricity consumption does not produce GHG emissions at the point of use, but in centralized plants where these electricity used to charge tricycle batteries has been generated. The Emissions & Generation Resource Integrated Database (eGRID), published by the U.S. Environmental Protection Agency is a worldwide recognized source of GHG emissions and other criteria pollutants data for the electricity generation in the United States [44]. The eGRID emissions factors are mainly valuable for GHG emissions assessments [45].

The eGRID output emission rates are related with the generation of electricity at the power plants, not with the electricity consumption; as a result, these values do not consider transmission and distribution losses, or imports and exports between subregions. However, eGRID provide grid gross loss factor that can be used to estimate emissions associated with these losses [44]. Emissions factors are taken from the eGRID database that includes transmission and distribution losses (USEPA, 2015b). The eGRID output emission rates and grid gross loss factor which accounts for transmission and distribution losses are shown in Table 3.

To account for variability in the electric generation profiles across the 50 states, three different electricity generation scenarios are considered: Table 2 shows the fuel profiles and emissions rates for three US cities: Portland, OR, New York, NY, and Denver, CO. As it is assumed that coal is the energy source with the highest emissions rates, these three cities are chosen to represent low, medium, and high percentages of coal-based electricity. The electric generation profiles of three U.S. cities are shown. New York has the “greenest” electricity generation in terms of CO2e, Denver has the “dirtiest”. Portland is below the USA average.

Emissions rates are provided for three GHG that are emitted in significant amounts due

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to the production of electrical energy: CO2, CH4, and NO2. Also, grid gross loss (GGL) factor are displayed in Table 3.

TABLE 4 Percentages of energy sources, grid gross loss factor and CO2e emissions rates for three US cities along with national averages. Source: US EPA

Region	GGL Factor (%)	Hydro (%)	Other renewable (%)	Nuclear (%)	Oil (%)	Gas (%)	Coal (%)	CO2 Emitted lbs./MWh	CH4 Emitted lbs./GWh	N2O Emitted lbs./GWh	CO2e Emitted lbs./MWh
Portland, OR	8.21	43.55	5.54	3.44	0.32	14.34	31.3	842.58	16.05	13.07	846.97
New York, NY	5.82	0.0	0.46	39.9	1.29	57.36	0.0	622.42	23.81	2.80	623.78
Denver, CO	8.21	3.91	5.71	0.0	0.04	17.15	72.99	1898.7	22.66	29.21	1906.2
US Averages	6.5	6.17	2.68	19.6	1.02	23.97	44.77	1232.3	24.14	18.26	1238.5

4.3.2 Tank-to-wheel: use phase modeling.

This is the tank-to-wheel (TTW) or utilization phase. The Tank-to-Wheel (TTW) considers the tailpipe emissions due to fuel consumption. The diesel fuel consumption value shown in Table 2 is based on the EPA's Fuel Economy estimates [21]. . In this study emissions related to vehicle maintenance are omitted because their value is negligible comparison with other life-cycle stages. A fuel economy of 18 miles per gallon is assumed during urban delivery operations, as shown in Table 2.

According to the EPA [46], the amount of tailpipe carbon dioxide emitted from burning one gallon of diesel is 10,180 grams of CO2. In 2011, the EPA estimated at 0.988 the ratio of CO2 emissions to total GHG emissions, in order to express carbon dioxide, methane, and nitrous oxide as carbon dioxide equivalents [47]. Therefore CO2e emissions are estimated as 22.72 lbs. CO2e/gallon of diesel. The amount of emissions in the utilization phase is a function of gallons consumed or distance traveled and fuel efficiency.

Hence, the use phase GHG emissions per mile [lbs/mile] are calculated for each vehicle using the following equations: [1] for electric tricycles and [2] for diesel commercial vans.

$$\frac{\mathrm{CO_2e}}{\mathrm{mile}} = \frac{\mathrm{kWh}}{\mathrm{mile}} \times \left(\frac{\mathrm{ERg}}{1 - \mathrm{GGL}} \times \frac{1}{\eta}\right) \quad [1]$$

$$\frac{CO_2e}{VMT} = \frac{1}{mpg} \times \left(\frac{CO_2e_{tailpipe}}{gallon} + \frac{CO_2e_{upstream}}{gallon}\right) \quad [2]$$

VMT = vehicle miles traveled

ERg = eGRID generation based output Emission Rate [lbs. / kWh]

GGL = eGRID grid gross loss factor [decimal]

η = charging efficiency [decimal]

4.4 Best and worst case scenarios

Using the data we collected from B-Line, we created two hypothetical scenarios to analyze the boundary emissions benefits of B-Line in comparison with a traditional diesel powered fleet.

- Scenario 1 (consolidation factor = 1): In the best-case, B-Line would provide the same services as it does now but instead of using tricycles, it utilizes diesel vans.
- Scenario 2 (consolidation factor = 0): In the worst-case, B-Line would not exist. Hence, each B-Line partner has its own commercial van for its logistics operations.

Given the pickup and delivery locations of each day, the researchers, together with B-Line operations manager, created hypothetical routes minimizing the global distance traveled for each scenario. As stated in the literature review, service time per customer using a van is likely to be greater than service time using a tricycle. This is due to the fact that tricycles can park on sidewalks while cargo vans have to find a secure location to park. Since 80 deliveries must be complied per day, and it is further assumed 10 minutes service time per customer, at least two vans are necessary to provide the same level of service in scenario 1. In scenario 2, it is assumed that each B-Line partner needs only one commercial van. In both scenarios not time windows or capacity constraints are assumed. This is due to the fact that commercial vans payload is much greater than tricycle payload. The result of minimizing distance is an average of 36 miles per day for the first scenario. In the second scenario one van coming from each partner's depot, makes its own deliveries and comes back to its depot. This results in 88 miles per day.

These calculations were taken within a conservative approach on an attempt to not underestimate a van's benefits in terms of distance traveled. To that end, neither logistics constraints are assumed, nor distance penalty to find a parking spot when making deliveries in downtown. Using the data from these two scenarios, we can calculate carbon footprint. Therefore, a comparison between B-Line's actual carbon footprint, against the footprint of a traditional diesel van delivery company can be made. That being said, important issues need to be highlighted.

- As stated in the methodology section, Carbon Footprint assessment, using GHG Protocol Scope 3, should also include all indirect emissions. This implies that GHG emissions caused by B-Line partners, while transporting goods from their respective warehouses to B-Line's depot, should be taken into account. In this approach, B-Line's partners' vehicles life cycle emissions were not considered. Only life cycle GHG emissions associated to the fuel consumed are included. From the eight partners B-Line currently delivers for, only two bring their products to B-Line' distribution center. It is calculated that on average, the daily distance covered by B-Line's partners, from their depots to the B-Line distribution center, is 25 miles. That should be taken into account to assess B-Line's carbon footprint, as well as in scenario 1. We assume B-Line's partners use a 15 mpg diesel van for covering those 25 miles.

- The life expectancy of common delivery vehicles is approximately 12 years [49]. Nevertheless, the life expectancy of freight tricycles is usually shorter and it is assumed to be 5 years.

- Life expectancy of Lead-Acid AGM batteries is between 3-10 years depending on use. Here it is assumed 4.

- Warehouse life cycle GHG emissions impacts are not included in this

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comparison. This is due to the fact that it is assumed that these facilities (space for loading and unloading, storage, park up vehicles overnight and walk-in cooler) are similar for both B-Line actual and scenario 1. This is a conservative approach because diesel vans are larger than tricycles, thus more space is needed to park overnight and to load/unload cargo.

4.5 Continuous approximation model

A continuous approximation model can be used to estimate total distance traveled by introducing logistics constraints. Dangazo (1984) proposed an approximation for capacitated vehicle routing problems (CVRP) and Figliozzi (2008) modified the approximation model for routes with a few customers per route. Tipagornwong and Figliozzi (2014) modified the approximation model to incorporate specific characteristics of tricycles. For instance, tricycles can deliver faster than traditional vehicles because they can be parked legally on sidewalks in front of the delivery location. In contrast, conventional vehicles need to spend time and distance to find and an available parking space. A new term was added to account for distance to find an empty parking space. The distance approximation is the following:

$$VRP = k_1 \frac{n-m}{n}\sqrt{nA} + 2\bar{r}m + n \cdot l_{park}$$

where

VRP = distance traveled for a fleet of vehicles (km);

$\bar{r}$ = distance between service area and a depot (km);

n = number of customers;

C = capacity of a vehicle (number of customer visits per vehicle);

m = number of vehicles,

A = size of service area (km^2)

k_1 = customer distribution coefficient.

l_{park} = average distance to find a parking space.

The parameter k_1 accounts for customers' location distribution and is a function of customers' density. Values of the k_1 coefficient can be calibrated empirically to the delivery service area; in this research the coefficient was calibrated to mimic B-Line's operation in terms of average daily total distance (82 miles), nine routes and five vehicles.

Access to parking seems to be a key variable to estimate emissions. In this research it is assumed that the driver of a delivery van have to either (i) cruise to find a free parking space or (ii) double-park illegally in front of the delivery destination. In case (i) there are additional emissions due the the additional distance traveled and also a time penalty is added to the route time; penalties of 200 feet and 3 minutes are assumed respectively. It is further assumed a fuel efficiency of 8 mpg due to the low speed while searching for parking, as shown in Table 2. In case (ii) there are additional emissions because the vehicle is idling while the customer is serviced. Distance and time penalty terms are not included, but a new term accounting for idle emissions is added directly into the emissions model. The estimated fuel consumption of an idling engine is 0.6 liters / hour per liter of engine displacement (Ecomobile, 2015). Hence, a 3.6 liter engine consumes 0.57 gallons / hour, as shown in Table 2.

4.6 Emissions and logistics model

Unlike previous research efforts, the model presented in this research include all stages in vehicle production and recycling and also incorporates logistics restrictions (delivery time, cargo, customer distribution) and parking characteristics of tricycles and vans. In addition, due to the small size and payload of electric tricycles, more than one tricycle can be replaced by a diesel delivery van. Hence, it is necessary to estimate what is is the number of vans that minimizes lifecycle emissions for this vehicle type.

The model presented in this section was utilized to estimate the number of vans that minimizes lifecycle emissions while satisfying all the logistics constrains that B-line vehicles must meet. The lifecycle emissions model is presented below. As explained in

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the previous section, B-line tricycle data was utilized to calibrate the parameter k_1.

SET

$I =$ Set of vehicle types, i belongs to the set of vehicle types, I ={van, tricycle}

DECISION VARIABLES

$R^i =$ Number of routes of vehicle i to serve all customers

PARAMETERS

$E^i_{tot} =$ Total emissions for vehicle i (lbs.CO_2e)

$e^i_{mat} =$ Emissions of material processing for vehicle i (lbs.CO_2e / lbs. vehicle)

$e^i_{prod} =$ Emissions of vehicle i production / disposal (lbs.CO_2e / lbs. vehicle)

$e^i_{bat} =$ Emissions of battery production / disposal (lbs.CO_2e / lbs. battery)

$e^i_{wtt} =$ Emissions of WTT phase for vehicle i (lbs.CO_2e / gallon or lbs.CO2e / kWh)

$e^i_{ttw} =$ Emissions of TTW phase for vehicle i (lbs.CO_2e / gallon or lbs.CO2e / kWh)

OTHER PARAMETERS

$c^i =$ Per – mile fuel or electricity consumed by vehicle i (mile / gallon or mile / kWh)

$c_{park} =$ Per – mile fuel consumed while finding a parking (mile / gallon)

$c_{idle} =$ Per – hour fuel consumed at idle (gallon / hour)

$m^i =$ Number of vehicles of type i to serve all customers

$l^i =$ Per – tour distance traveled to serve route of vehicle type i (miles / tour)

$w^i_{tar} =$ Vehicle i tare weigh (lbs.)

$w^i_{bat} =$ Battery weigh (lbs.)

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$b^i =$ Number of batteries

$w_{cap}^i =$ Payload capacity for vehicle i (lbs.)

$w_d =$ Average unit customer demand (lbs.)

$v_{in}^i =$ Average speed of vehicle i running inside service area (mph)

$v_{out}^i =$ Average speed of vehicle i running outside service area (mph)

$t^i =$ Total route time of vehicle i (hours)

$t_{ser}^i =$ Average customer service time from vehicle i (hours)

$t_{max} =$ Maximum daily working time (hours)

$y^i =$ Life expectancy of vehicle i (years)

$y^b =$ Life expectancy of batteries (years)

$d_{year} =$ Days of service per year

OBJECTIVE

Minimize total emissions = material assembly, production & disposal + battery material, production & disposal + use phase + find parking (only first scenario) + idle service time (only second scenario)

$$E_{tot}^i = \frac{\left[\left(e_{mat}^i + e_{prod}^i\right)m^i \cdot w_{tar}^i\right]}{y^i} + \frac{d_{year}\left[e_{bat}^i \cdot b^i \cdot w_{bat}^i\right]}{y^b} + \frac{d_{year}\left(e_{wwt}^i + e_{ttw}^i\right)R^i \cdot l^i}{c^i} + h\frac{d_{year}\left(e_{wwt}^i + e_{ttw}^i\right)n \cdot l_{park}^i}{c_{park}} + j d_{year}\left(e_{wwt}^i + e_{ttw}^i\right)n \cdot t_{ser}^i \cdot c_{idle}$$

[1]

$$l^i = \frac{k_1 \frac{n - m^i}{n}\sqrt{nA}}{R^i} + 2\bar{r}$$

[2]

$$t^i = \frac{k_1 \frac{n - m^i}{n} \sqrt{nA}}{R^i \cdot v^i_{in}} + \frac{2\bar{r}}{v^i_{out}} + n \cdot t^i_{ser} + h \cdot n \cdot t^i_{park}$$

[3]

$$m^i \geq \frac{R^i \cdot t^i}{t_{max}}$$

[4]

Subject to

$$R^i \geq \frac{n \cdot w_d}{w^i_{cap}}$$

[5]

$t^i \leq t_{max}$ [6]

$b^i \geq 2m^i$ [7]

$R^i \in$ Set of positive integers (natural number) [8]

$m^i \in$ Set of positive integers (natural number) [9]

$h = 1$ For the first scenario, otherwise = 0 [10]

$j = 1$ For the second scenario, otherwise = 0 [11]

Equation 1 is the objective function. Equation 2 is the length of a route, starting from a depot, serving customers, and returning to the depot. Equation 3 is the duration of a vehicle route. Equation 4 is the minimum number of vehicles needed to serve all customers. Equation 5 is the vehicle route capacity. Equation 6 is the working time constraint. Equation 7 is the minimum number of batteries for a tricycle. Equations 8 and 9 restrict the number of vehicles and routes to the set of positive integers. Equations 10 and 11 make one scenario at a time.

5. Results, Discussion and Conclusion

5.1 Best and worst case scenarios

This section present the results of the B-Line GHG emissions assessment compared against the GHG emissions of traditional pick-up and delivery companies in the two boundary scenarios. Scenario 1 is the best-case: cargo is consolidated in B-Line distribution center and then delivered using diesel vans. Scenario 2, the worst-case, cargo is dispersed and each company has its own commercial van for its logistics operations.

Figure 2 shows that CO2e emissions as a result of tricycle delivery system fall between 51% and 72%, depending on the cargo consolidation factor. That is using the Portland electricity emissions rate. However, large emissions savings can be appreciated even in the case of carbon-intensive electricity generation, where GHG emissions are reduced by at least 46%.

However, distance traveled increase substantially. As has been stated, B-Line daily mileage account for 82 miles, plus 25 miles covered by its partners. If B-Line service were provided with vans, they would travel 36 miles. That results in a reduction of 50% of miles traveled, as a result of the tricycle's smaller loads and volume capacity.

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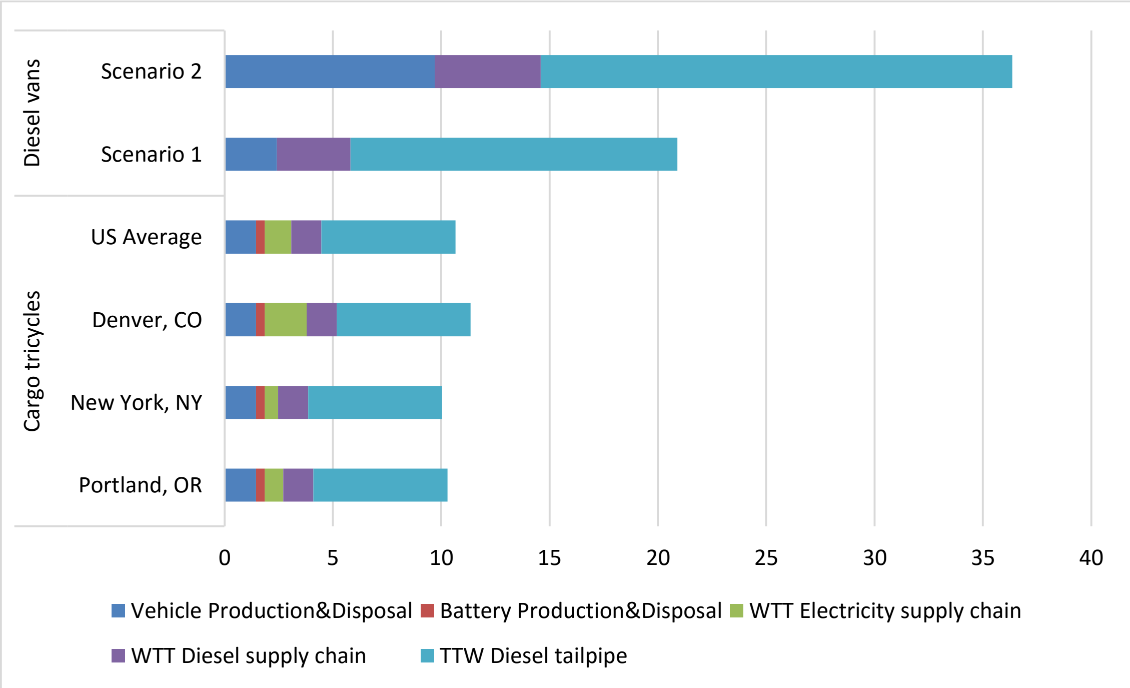

FIGURE 2 CO2e emissions / year [metric tons]

B-Line avoids between 10 and 26 tons of CO2 emissions per year. However, most of GHG emissions are caused by B-Line partners while transporting goods from their respective warehouses to B-Line's depot. These 25 miles per day account for more than 64% of the B-Line GHG emissions. If in our approach, we account for all indirect emissions from consumption of purchased fuels and electricity, transmissions and distribution losses, vehicle production and disposal, but we do not consider emissions from B-Line's partners operations, a greater difference between a tricycle logistics company and a traditional one could be achieved.

Figure 3 shows CO2e emissions per delivery. The impact of partners' emissions on B-Line's carbon footprint can be observed. If partner's transport activities are not included, a huge reduction can be appreciated: 6 tricycles and 12 batteries have 80% less environmental impact in terms of CO2e emissions than 2 common diesel cargo vans.

Moreover, if partners' transport activities are not included, variations between different electricity generation profiles can be observed. For instance, if B-Line were operating in Denver, it would emit 28% more GHG emissions. If there were two companies like B-Line one in Denver and the other in New York City, that one operating in Denver would emit 35% more GHG emissions than its counterpart.

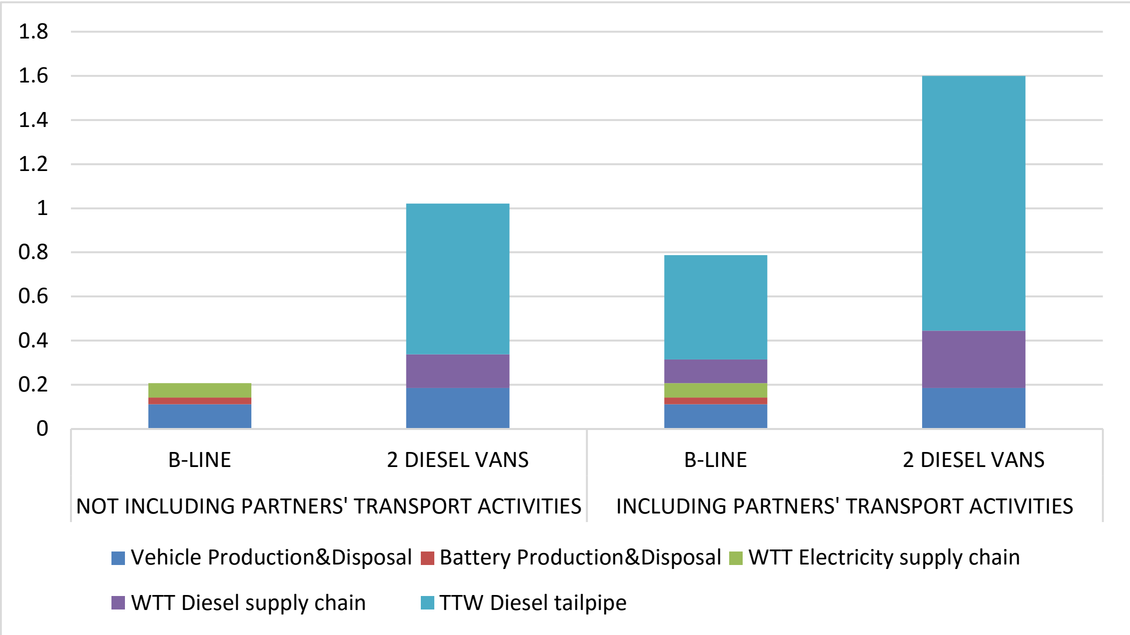

FIGURE 3 CO2e emissions / delivery [lbs.]

5.2 Results of the Continuous Approximation Model

This section presents the results of the GHG emissions comparison in the two scenarios. Then, an elasticity analysis is conducted to find the key parameters which affect total emissions.

Nine tricycle routes are needed to serve all customers: four tricycles make two routes and one tricycle just makes one. On the other hand, three vans can serve all customers by doing just one route each. Even though the distance traveled by vans is smaller, the total emissions are several times higher.

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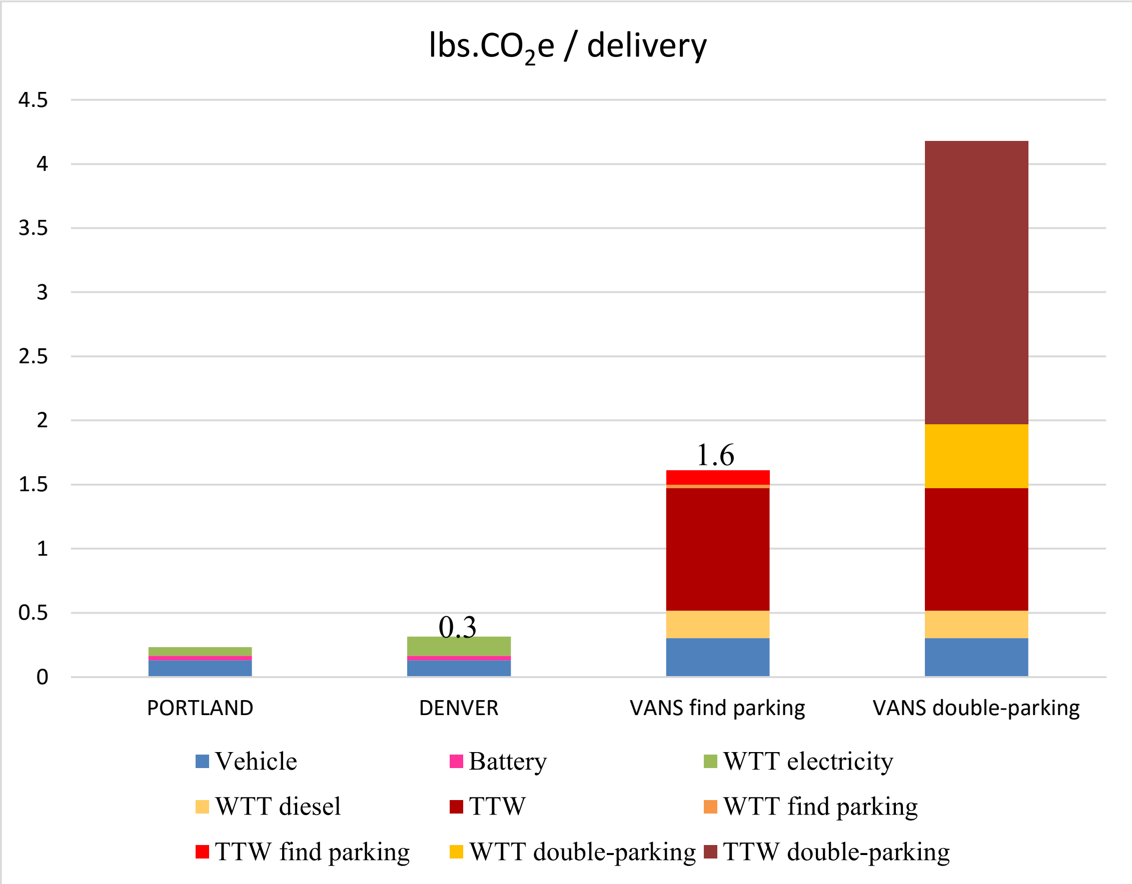

FIGURE 4 Emissions per customer in lbsCOe/customer

The total daily distance traveled by diesel vans is 63 miles (of which 3 miles are extra distance to find parking), almost a 25 percent less than the distance traveled by tricycles. Because of the tricycle's lower payload, a tricycle route has fewer deliveries and is shorter.

Figure 2 compares total emissions per customer in pounds of CO2e. The left columns represent lifecycle tricycle delivery emissions and the right columns lifecycle van delivery emissions. The third column represents van emissions when vans travel 200 ft to find parking; the fourth column represent van emissions when vans double park and idle. Tricycle lifecycle emissions are substantially lower than van lifecycle emissions. Even the emissions using "dirty" electricity are at least five times lower than van emissions. Utilizing Portland's electricity generation profile, tricycle emissions due to electricity consumption (operating emissions) only account for 28% of total tricycle emissions. The remaining 72 percent are due to tricycles and batteries production and recycling. Using Denver's electricity generation profile, operating emissions account for 47%. By contrast, in the case of diesel vans, operating emissions (due to fuel consumption) represent 82% of the total emissions in the first scenario, and more than 92% in the second scenario.

Figure 3 shows proportions of emissions per customer of diesel vans and tricycles in both scenarios.

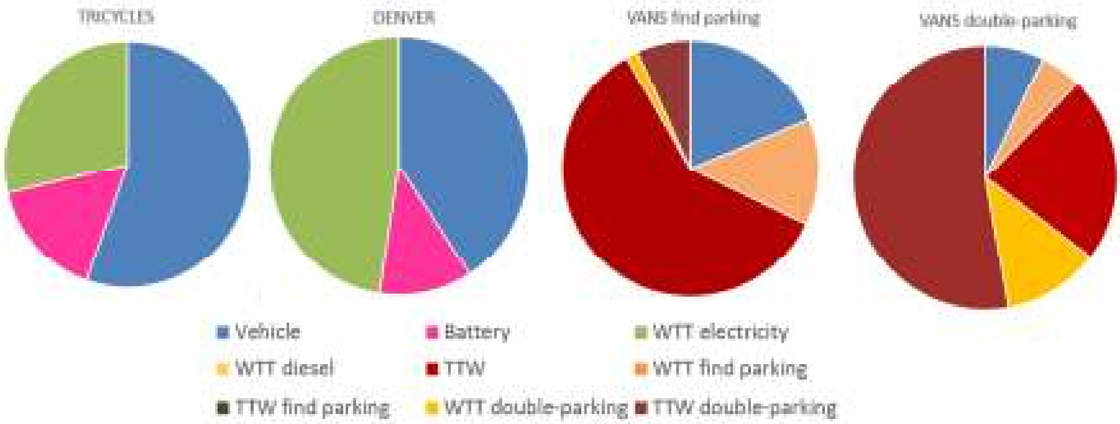

FIGURE 5. Proportions of emissions/customer

Idling can have a highly significant impact in urban logistics when the routes have many customers and customers are nearby; vehicles spend more time at the customers than actually traveling between customers. Because customers service time is 10 minutes on average a total of 4.5 hours of idling time per day per van was calculated.

Another important outcome of this study is that from the first time, to the best of the authors' knowledge, electricity consumption during electric-tricycles operations has been measured: 48.65 watt-hour per mile, or 20.55 miles per kilowatt-hour. Diesel vans fuel economy is assumed to be 18 miles per gallon. The EPA estimates that the energy content of one gallon of diesel is equivalent to 33.7 kWh, and that makes diesel fuel economy of 18 mpg equivalent to 0.53 miles per kilowatt-hour. This makes B-line tricycles almost 40 times more energy efficient than diesel vans.

5.3 Elasticity Analysis of per customer emissions

An elasticity analysis is useful to understand what variables are likely to affect total lifetime emission changes. All parameters in the elasticity analysis are related to logistics and transportation constraints, as shown in Figure 4.

Emissions are very sensitive to number of customers or number of daily deliveries and customer distribution because these variable increases significantly the distance traveled. The emissions of vans are very sensitive to fuel efficiency but when vans double park (D-P) the elasticity value is almost 1/3 lower. When vans double park emissions are very sensitive to fuel consumption while idling and the service time duration. In general, any variable related to distance traveled affect more vans than tricycles, except for distance between depot and service area. Tricycles return more often to the depot (shorter routes), hence they are penalized for this additional distance.

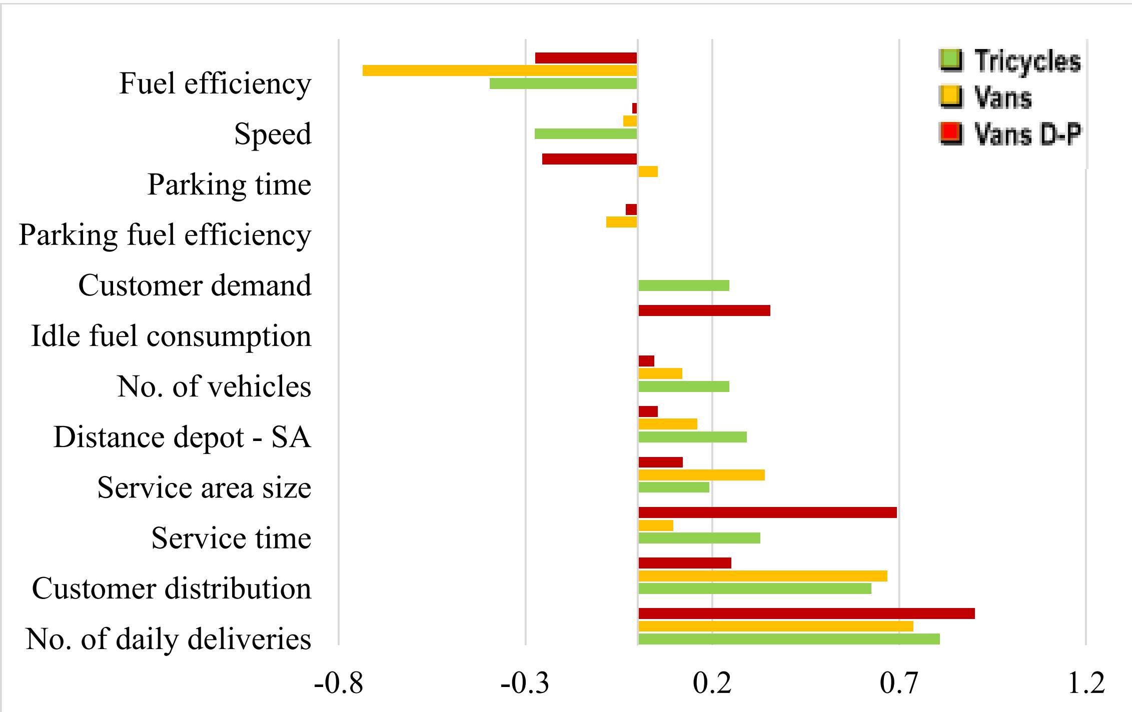

FIGURE 6. Per customer emissions elasticity analysis.

5.4 Discussion

A conservative approach has been taken in order to no overstate emissions savings. Diesel van fuel economy, the most elastic variable, is often lower than 15mpg when operating in congested urban areas. Moreover, extra distance traveled searching and finding a parking (and the resulting emissions) are not considered. Nor is account taken emissions resulting of motor idle while waiting for a parking or when double-parking, although these emissions are significant [14].

However, the results show a high reduction of greenhouse gas emissions by replacing diesel vans with electric tricycles. Using Portland electricity mix, CO2e emissions fell by at least 51%. But even in a region with a large electricity emission rate, CO2e emissions are cut by half compared to traditional delivery vehicles. These emissions reductions are similar to other research efforts. Browne et al. [15] evaluated the use of an urban distribution center and electric vehicles in London and came to the same conclusion. CO2e emissions were cut by a 54%.

While city location is not relevant, high urban density and congestion level are extremely important because in that conditions traffic speed and miles per gallon are reduced, emissions and route time increased, which can lead to more commercial vehicles needed.

In those congested areas, where traditional freight transport externalities are especially unreasonable, tricycle competitiveness and benefits are maximized. In fact, the more congested an urban area is, the more advantage for tricycle logistics services. Due to the fact that tricycles service time is shorter but their speed is lower, they are more efficient when delivery points are more densely located. In fact, emissions reductions per delivery seems to be higher when delivery points are close to each other. This is work for a future research effort.

Trends in sustainable logistics chains is to minimize CO2e per parcel. For that purpose, a large truck as well as a cargo tricycle make sense if fully loaded, but capacity inefficiencies must be eradicated. Hence, urban consolidation centers are needed on the edge of downtown to switch cargo from trucks to tricycles o small electric vehicles, which suit better for urban deliveries.

Therefore, urban local authorities which are concerned about sustainability, public health and livability of their residents, must push for the use of small electric freight vehicles. Tricycles should have tax breaks and other incentives, like exclusive delivery zones, turn traffic into pedestrian areas, so tricycles can achieve economies of scale.

In this study only GHG emissions are analyzed, but is important to highlight the contribution of cargo tricycles to the reduction in air pollution. Tricycles can improve cities' air quality, not only because their lack of tailpipe emissions, but also because emissions are shifted to centralized power plants far from the cities. Other environmental benefits of tricycles are reduction of traffic congestion, because of their small size, and increase pedestrian safety.

However, as stated before, tricycle logistics services need make more routes to provide the same level of service, and most of the emissions are due to the partners' transportation activities. Only two of the B-Line eight partners make this intermediate link, but their emissions account for 64% of total B-Line emissions.

5.5 Conclusion

This research studies the environmental benefits of tricycle logistics services in urban freight distribution of food and office supply. The paper has analyzed the carbon footprint of a tricycle logistics company in comparison with a typical diesel delivery company. To the best of the authors' knowledge, there is no published carbon footprint assessment of a tricycle logistics company in the existing literature.

In our first approach, the researchers, together with B-Line operations manager, created hypothetical routes minimizing the global distance traveled for each scenario given the pickup and delivery locations of each day. The results show that B-Line reduce between 10 and 26 metric tons of CO2e emissions each year, depending on cargo consolidation factor. The evaluation has also indicated that the emissions rates from purchased electricity have negligible impact on the overall emissions. Limitations

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are boundary scenarios. A more accurate estimation could not be calculated, because there is not data. However, real approximation it is likely to be close to best-case scenario, in which 51% of emissions reductions are estimated.

In our second approach, a continuous approximation model is utilized to create optimal routes to serve all customers, given a set of time and capacity constraints. Results show that emissions per customer are at least 5 times smaller when tricycles are utilized. With Portland's electricity profile, tricycle lifecycle CO2e emissions per customer are around seven times smaller than diesel vans lifecycle CO2e emissions per customer. Utilizing the "dirtiest" USA electricity generation profile lifecycle CO2e emissions per customer are five times smaller when tricycles are utilized.

High urban density and congestion levels are important factors because in these conditions traffic speed and miles per gallon are reduced, emissions and route time increased, which can lead to diesel commercial vehicle fleets to emit more GHG emissions. In dense congested areas where freight transportation externalities are high, tricycle competitiveness and benefits are maximized. High customer density is one of the most important variables to reduce emissions. Due to the fact that tricycles service time is shorter and their speed is lower, dense congested urban areas where transportation externalities are higher, maximize tricycles' environmental benefits. Higher congestion levels, lower road capacity, and extensive bicycle networks improve tricycle logistics services environmental benefits and competitiveness. Idling at customers can drastically increase vans emissions.

Local and state governments which are concerned about freight urban transportation externalities should incentive the use of small electric vehicles in urban delivery operations. On a per mile basis, tricycles have CO2e emissions rates that are 40 times smaller than vans' CO2e emission rates. To minimize CO_2e per parcel capacity inefficiencies must be eradicated. Hence, urban consolidation centers are needed on the edge of downtown to switch cargo from trucks to tricycles o small electric vehicles. In this study only greenhouse gases which affect global warming are estimated, but it is important to highlight the contribution of tricycles logistics services to improve cities' air quality by shifting tailpipe emissions from downtown areas to more remote power plants.

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In summary, this research has analyzed the carbon footprint of a tricycle logistics company and compared the results with the carbon footprint of a typical diesel powered delivery company. The results show that electric tricycles can reduce CO2e emissions between a 50% and 70% depending on the cargo consolidation factor. The evaluation has also shown that electricity emission profile have negligible impact on the overall life cycle emissions. State and local governments which are concerned about sustainability, public health and livability should incentivize the use of small electric freight vehicles. Tax breaks and other incentives like exclusive delivery zones and large pedestrian areas can tip the economic balance in favor of small electric vehicles.

Future research effort could be to analyze tricycles efficiency and emissions when delivery points are more densely located. Also to analyze other environmental benefits like space and congestion impact, understand traffic performance.

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Anexo I. TRB Paper

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AN ASSESSMENT OF THE CARBON FOOTPRINT REDUCTIONS OF TRICYCLE LOGISTICS SERVICES

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ABSTRACT
This paper assesses the greenhouse gas emissions of a tricycle logistics company (B-Line) which is currently providing last mile distribution service in downtown Portland, OR. The main research goal is to compare carbon footprint between tricycle logistics services and a traditional urban logistics company. The tricycles utilize electric engines whereas traditional urban logistics vehicles utilize diesel powered vehicles. Emissions associated with power and fuel consumption, along with vehicle and battery production, assembly and disposal were quantified. Real-world GPS and warehouse data were recorded to evaluate B-Line operations. Different scenarios were analyzed to assess boundary emissions benefits. The results show that the total greenhouse gas emissions, expressed as CO2 equivalent, are reduced between 51% and 72%. To account for variability in the electric generation profiles across the 50 states, three different scenarios are considered to represent low, medium, and high carbon-intensity electricity generation.

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INTRODUCTION

Cities need more than ever to be sustainable in order to achieve a better quality of life for their citizens. According to a United Nations report launched in 2014, 54% of world's population now lives in urban areas [1]. In United States, over 80% of the population already lives in urban areas (United States Census, 2012) [2]. Due to urbanization and more frequent deliveries commercial vehicles and traffic are steadily increasing [3]. The Federal Highway Administration (FHWA) states that there has been an increase of 21% in terms of total vehicle miles of travel (VMT) within urban areas from 1996 to 2006. More specifically, a faster growth of freight traffic in urban areas has been detected; the share of freight vehicles increased from 4.8% to 5.2%.

Roadway capacity and parking spaces are very limited in dense and congested urban areas. Considering that passengers and freight transportation compete for the same space, trends in logistics (higher frequency of deliveries and smaller order size because of just-in-time systems) are now increasing negative transportation externalities like traffic congestion, poor road safety, crashes, energy consumption, air and noise pollution, and overall miles traveled.

Several empirical studies confirmed that urban freight vehicles account for 6-18% of total urban travel [4] [5]. Furthermore, 21% of CO_2 emissions come from urban freight vehicles [6] [7]. Taking into account that the transportation sector is responsible for 28% of total greenhouse gas (GHG) emissions in the United States, the contribution of the urban freight transportation is extremely relevant. In addition, urban freight vehicles (commonly diesel) are known to seriously affect public health. Diesel motor vehicles are a major source of air contaminants produced during the diesel combustion, like Mono-nitrogen oxides (NOx), which react to form smog and acid rain [8]. There are other air contaminants that increase health risks such as sulfur oxides (SOx), carbon monoxide (CO) and particulate matter (PM) [9].

Governments are seeking to mitigate freight negative externalities by cutting GHG emissions and other air pollutants. One possible strategy to tackle the negative effects of urban freight is the electrification of urban delivery vehicles [10]. In congested urban areas, delivery trucks have low fuel economy because they spend a great portion of their time idling [11]. In addition, electric motors provide higher efficiency than internal combustion engines in a urban environment in which average driving speed is low [12]. Another advantage is that systematic recharging or battery swapping are feasible because these delivery vehicles make similar routes every day and after each route return to the company garage [13]. Hence, the switch from a fossil fuel combustion fleet to an electric-powered fleet seems like a suitable solution to reduce urban emissions. One of the great advantages of vehicles electrification is that it would couple the transportation and the electric sectors and shift emissions from the vehicles in urban areas to remote power stations, improving cities' air quality.

In particular, electrically-assisted cargo tricycles could play a role in reducing GHG emissions from the freight transportation sector. Cargo tricycles are an ideal low-emission alternative to transport light goods in city centers not only because their lack of tailpipe emissions, but also because their small size and easy access to compact, congested towns and cities. Unlike conventional diesel-powered vans, cargo tricycles can legally use bicycle paths and lanes allowing for faster access to congested downtown or pedestrian areas [14]. Cargo tricycles operations are not significantly affected by congestion or lack of loading/unloading parking areas. Other advantages are noise reduction through the use of quieter vehicles, improved safety for pedestrians and less conflicts in traffic with passenger cars and other road users in general [15].

Although past and current research efforts into cargo tricycles benefits are extensive, most research efforts have ignored vehicle production and disposal emissions when evaluating environmental impacts. To the best of the authors' knowledge, there are no published carbon footprint assessment of a tricycle logistics company in the existing literature.

This research explores the greenhouse gas (GHG) emissions saving potential of electric urban delivery tricycles over their life time for urban delivery operations. B-Line [16] is a tricycle logistics company that is currently providing warehousing, pick-up, and delivery services in downtown Portland, OR. The researchers were able to record and analyze several days of detailed B-Line GPS route and warehouse data. The goal is to compare B-Line's carbon footprint against the footprint of traditional pick-up and delivery companies. Because the freight that is delivered by tricycle is often light and small, diesel vans are the natural competitor.

Although electric tricycles do not produce tailpipe emissions, greenhouse gas (GHG) emissions from electricity generation are substantial. And even though electric tricycles may have greater tank-to-wheel (TTW) efficiency than conventional diesel-powered vans in city delivery operations, the overall energy efficiency of electric tricycles depends on life-cycle energy use including upstream electricity generation and transmission efficiency. An assessment of tricycle and diesel van life cycle emissions is carried out, ranging from extraction of raw materials from the earth to vehicle manufacturing, use stage, and recycling/disposal at the end. For the use phase, B-Line operations are analyzed to study how that delivery services could be provided by more traditional diesel powered fleets.

The next section presents a brief literature review, and the following sections present the methodology used to compare different vehicle technologies, case study, and results.

LITERATURE REVIEW

In order to understand the topic of tricycle logistics service, it is essential to break down and analyze the characteristics of cargo tricycles, and also to quantify their environmental effect in the role they play as last-mile vehicles in urban distribution.

Characteristics of Cargo Tricycles

Cargo tricycles are often electric-assisted. La Petite Reine and Cycles Maximus are two important manufacturers of cargo tricycles. On a regular basis, the tricycle payloads are within 331lbs and 600 lbs, and their maximum speed is approximately 10 mph [17]. Differences between cargo tricycles and diesel vans can be identified in Table 1, where vehicles specifications of a typical cargo tricycle and van are shown.

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TABLE 1 Specifications of Typical Diesel Van and Tricycle

Specification	Electric tricycle Cycles Maximus	Diesel cargo van GMC Savana 2500
Price	6,200 dollars [a]	41,500 dollars [b]
Battery size / Tank size	864 watt – hour [a]	31 gallons [b]
Battery capacity	72 - 92 Ah [a, c]	-
Gross Vehicle Weight Rate	1,100 lbs [d]	8,600 lbs [b]
Curb Weight	500 lbs [d]	6,118 lbs [b]
Battery Weight	77.8 lbs [c]	-
Max Payload	600 lbs [d]	2,482 lbs [b]
Cargo Volume	60 ft3 [d]	239.7 ft3 [b]
Range	30 miles [a]	465 miles [e]
Max Speed	10 mph [f]	50 mph [h]
Fuel economy (city)	25 – 50 watt-hour/mile [d]	15 mpg [g]

[a] Cycles Maximus [18]
[b] GMC Vans Savana Cargo [19]
[c] Odyssey Batteries [20]
[d] Provided by B-Line [16]
[e] Based on the fuel economy.
[f] Conway et al. [17]
[h] Typical urban area maximum speed.
[g] 2014 Vehicle Technologies Market Report, US Department of Energy [21]

Cargo tricycles have many advantages. Because their small size, tricycles require minimal parking space and can be parked legally on- and off-street, on sidewalks or inside business [14]. A diesel van would need to park-on-street, increasing the walking time and distance to make a delivery, and commonly requiring the vehicle to idle while waiting for parking. The driver of a delivery van have either to cruise for a free parking space or double-park illegally, and this increase cost, emissions, and traffic congestion. Using tricycles, customer service times can be reduced.

In terms of maneuvering throughout urban areas, tricycles also tend to have a distinct advantage, because there are dedicated bicycle lanes a tricycle can use to bypass traffic congestion at all times. Furthermore, the possibility of simplifying and shortening the route by crossing pedestrian areas or riding up one-way streets on a sidewalk in the opposite direction makes a tricycle the perfect vehicle to deliver in dense downtowns. Lastly, a tricycle has better fuel economy in terms of energy, because of its lower weight and because riders have to pedal. Wilson et al. [22] state that an average fit man or woman could pedal a bicycle with the power output of 75 watts without suffering fatigue for 7 hours. The human contribution is not insignificant, because power exerted by the rider could reduce necessary battery size by around 500 watt-hours during a 7-h day, and battery capacity is around 850 watt-hours.

Although there are many advantages to cargo tricycles, there are also several disadvantages. Since tricycles have limited payloads and volume capacities, there are times where freight is not deliverable due to it exceeding the vehicles limit, both in weight or volume. Limited travel range and low speed in free-flow conditions are also crucial disadvantages. Therefore, tricycles only fit as an urban delivery vehicle in

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certain contexts, that is, small volumes and low weight parcels when a diesel van delivery process is constrained by the limitations of the urban structure.

Decarbonizing the last-mile

Cargo tricycles are mostly used in the 'last mile' of the logistics chain, defined as the distribution of goods from an urban distribution center to final customers. To date, the existing research efforts into the use of cargo tricycles within urban 'last mile' logistics are still scattered [23] [24] [25]. Most of the studies are limited to the European context, since cargo tricycle delivery is better suited to the narrow streets of the old town. Popular examples are located in Brussels, London and Paris [17] [26].

Most research effort has been focused on identifying the market niche within logistics sector [23]. In terms environmental effects, the body of research is relative scarce. However, there are some studies and some companies which have put across emissions savings data. For instance, GNewt Cargo [27], a green delivery company in London, has been independently verified to cut CO_2 emissions per parcel delivered by 62%, according to their website. Ecopostale [28], a Belgium company, estimates 29 tons of CO_2e savings, comparing their delivery service against a traditional delivery company; and Txita [29], a tricycle delivery company of San Sebastian (Spain) estimates the saving in CO_2e, compared with the use of commercial vans, at 14 tons, based on 59,247 parcels delivered in two years. A Dutch study [30] estimated possible annual savings for the Netherlands of 21,000 tons of CO_2.

Browne et al. [15] evaluated a trial in which office supply was delivered from a suburban London depot to final customers in downtown. During the trial diesel vans were replaced by small electric vans and tricycles operated from a Micro-Consolidation Center close to downtown. A truck journey was needed to transport cargo from suburban London to the distribution center in downtown London. Then, 6 tricycles and 3 electric vans delivered the cargo from the distribution center to final customers. The operation of these electric vehicles did not result in any fossil fuel consumption or greenhouse gas emissions because the electricity used by these electric vehicles was produced from renewable sources. The result showed great benefits: total distance travelled was reduced by 20% and the CO2e emissions per parcel fell by 54%. GNewt Cargo [27], was the operator of the micro-consolidation center, tricycles and electric vans.

Conway et al. [31] evaluated two case studies in NYC, assuming that Cycles Maximus cargo tricycles replaced daily operation of five-year-old cargo van. Total annual CO2 and PM10 savings are 19-21 tons and 3.5-4 lbs. respectively, due to cargo tricycles operations in NYC. Because the Cycles Maximus vehicles in use by the case study operators were fully human-powered, emissions savings were evaluated by estimating emissions rates for the comparative motorized urban delivery vehicles using the EPA's MOVES model [32]. Unlike this research, a life cycle assessment and a comparison with alternative diesel vehicles was not performed.

METHODOLOGY

A Carbon footprint (greenhouse gas emissions assessment) quantifies the total emissions that contribute to global warming caused by an organization or project [33]. The assessment quantify GHG emissions of carbon dioxide, methane and mono-nitrogen oxides and then converts these emissions into carbon dioxide equivalents (CO_2e), typically with a time horizon of 100 years using the global warming potential values recommended by the Intergovernmental Panel on Climate Change [34].

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The GHG Protocol is the "most widely used international accounting tool for government and business leaders to understand, quantify, and manage greenhouse gas emissions", according to the GHG Protocol website [35]. The GHG Protocol defines direct and indirect emissions differentiating whether they are emissions from sources that are controlled by the company studied, or they are consequence of the company studied but occur at sources controlled by other organizations. Three broad scopes are also defined: [I] All direct GHG emissions. [II] Indirect GHG emissions from consumption of purchased heat or electricity; and [III] Other indirect emissions, such as the extraction and production of purchased materials and fuels, transport operations in vehicles not controlled by the organization, electricity-related activities (e.g. transmission and distribution losses), outsourced activities, etc.

This study includes GHG emissions associated with energy use and fuel consumption, along with vehicle and battery production, use and disposal, in an attempt to estimate the most comprehensive possible Carbon Footprint assessment. In this context, Life cycle assessment (LCA) of systems should be introduced. LCA (also known as a 'cradle-to-grave' assessment) assess multiple environmental impact categories, which may include global warming of GHG emissions, but may also include human health impacts, ecosystem and resources impacts, land use, etc. While Carbon Footprint separates out the inputs into three scopes, LCA commonly separates the inputs into life cycle phase (ranging from extraction of raw materials from the earth to manufacturing, distribution, product use, and recycling/disposal at the end). Life cycle stages should be analyzed from the perspective that each stage depends on the one before it. LCA helps to avoid shifting environmental problems from one place to another, by considering the entire life cycle system.

In this research we compare the Carbon Footprint of a tricycle logistics company against the footprint traditional pick-up and delivery companies covering the broadest GHG Protocol scope; that is, including all life cycle emissions associated with the production, use and disposal of vehicles. The two commercial vehicles are as follows: a conventional internal-combustion (IC) diesel-powered cargo van such as the GMC Savana 2500 and an electric-powered cargo tricycle such as the Cycles Maximus cargo trike. Vehicle specifications are shown in Table 1. We examine commercial vans and electric tricycles in three distinct phases: [I] vehicle cycle (from raw material extraction to disposal considering different vehicle compositions); [II] well-to-tank (fuel/electricity production and distribution); and [III] tank-to-wheel (vehicle use operation, where only fossil fuel vehicles produce tailpipe emissions.). To execute a LCA, several software tools are available. For transportation analyses in particular, GREET [36] is a widely known option. Other data used in this study is collected from publicly available sources such the U.S. Environmental Protection Agency [37] and, the eGRID database [38].

Vehicle life cycle

There are several stages on the vehicle life cycle: extraction of raw materials (including aluminum, iron, plastic, copper), transport to factories where alloys are developed, refinement of raw materials and production of final materials, transportation of those materials to assembly plants, production of vehicles at the vehicle assembly factories, transport and distribution of vehicles to dealers, and lastly, disposal or recycling. To estimate GHG emissions from vehicle manufacturing (not including the tricycle battery), we use the GREET 2014 model [36]. Detailed environmental impacts are provided for numerous materials and manufacturing processes, the GREET model

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breaks down different vehicle technologies into their constituent systems, components and parts considering mass and material composition. Those breakdowns are obtained from a large number of reports.

The functional unit selected is mass (lbs.) of each vehicle, both for raw material recovery, processing and fabrication, and for vehicle component production, assembly and disposal/recycling. The material composition of each vehicle type is estimated with the GREET vehicle cycle by using real weights shown in Table 1. In our approach we consider an electric cargo tricycle as a pick-up truck (EV conventional material) and a commercial diesel van as a pick-up truck (ICEV conventional material). Vehicle life cycle GHG emissions are 2,677 lbs. of CO_2e for a Cycles Maximus cargo tricycle and 32,073 lbs. of CO_2e for a GMC Vans Savana Cargo diesel van.

Battery life cycle

Electric-tricycles typically use Lead-Acid (PbA) batteries. Although Lead-acid is the oldest type of rechargeable battery, is still attractive due to their low cost and high specific power. Valve-regulated lead-acid (VRLA) do not require constant maintenance, unlike the initial "flooded" design. AGM dominates the VRLA market share, due its extremely high Energy/Weight density and excellent overall performance. Sullivan and Gaines [39] conducted a full process-based life-cycle analysis (LCA) of VRLA battery. In comparison with other battery technologies, the PbA battery has the lowest cradle-to-gate (CTG) emissions footprint, because of its highly successful recycling processes and infrastructure [40]. Currently, new PbA batteries range from 60% to 80% recycle content (Battery Council International 2010). Rantik [41] analyzed the recycling processes of PbA battery. Using the GWP values recommended by the International Panel on Climate Change to convert CH_4 and N_2O, it is estimated that battery life cycle GHG emissions are 3.93 $kgCO_2e/kg$ of PbA battery.

Use phase

The majority of life cycle GHG emissions are emitted during the use phase. In this carbon footprint comparison between electric-tricycles and commercial vans, emissions from vehicle maintenance are omitted assuming to be similar or that the difference is minimal in comparison with other life cycle phases.

Well-to-Tank: emissions of energy supply chain.

<u>Diesel fuel supply chain</u>

Life cycle GHG emissions for a typical fuel such as diesel include several stages: from petroleum pumping, extracting, transporting, refining in factories, dispensing and distributing through to diesel stations. The diesel supply chain is the most polluting stage on the life cycle of a vehicle [42]. It has been estimated that around 20% of the life cycle GHG emissions of fossil fuels like petrol and diesel are emitted during extraction, transport and refining processes [43]. The U.S. average mix of diesel fuel, from GREET model [36], is used for the Well-To-Tank (WTT) modelling of ICE vehicles. These upstream GHG emissions were estimated to be about 5.108 lbs. of CO_2e per gallon of conventional diesel US refineries average.

<u>Electricity supply chain</u>

Electricity consumption does not produce GHG emissions at the point of use, but in centralized plants where these electricity used to charge tricycle batteries has been produced. The Emissions & Generation Resource Integrated Database (eGRID), published by the U.S. Environmental Protection Agency is a worldwide recognized source of GHG emissions and other criteria pollutants data for the electricity generation in the United States [44]. The eGRID emissions factors are mainly valuable for GHG emissions assessments [45].

The eGRID output emission rates are related with the generation of electricity at the power plants, not with the electricity consumption; as a result, these values do not consider transmission and distribution losses, or imports and exports between subregions. However, eGRID provide grid gross loss factor that can be used to estimate emissions associated with these losses [44]. To account for variability in the electric generation profiles across the 50 states, three different electricity generation scenarios are considered: Table 2 shows the fuel profiles and emissions rates for three US cities: Portland, OR, New York, NY, and Denver, CO. As it is assumed that coal is the energy source with the highest emissions rates, these three cities are chosen to represent low, medium, and high percentages of coal-based electricity. Emissions rates are provided for three GHG that are emitted in significant amounts due to the production of electrical energy: CO_2, CH_4, and NO_2. Also, grid gross loss (GGL) factor are displayed in Table 2.

TABLE 2 Percentages of energy sources, grid gross loss factor and CO2e emissions rates for three US cities along with national averages. Source: US EPA

Region	GGL Factor (%)	Hydro (%)	Other renewable (%)	Nuclear (%)	Oil (%)	Gas (%)	Coal (%)	CO2 Emitted lbs./MWh	CH4 Emitted lbs./GWh	N2O Emitted lbs./GWh	CO2e Emitted lbs./MWh
Portland, OR	8.21	43.55	5.54	3.44	0.32	14.34	31.3	842.58	16.05	13.07	846.97
New York, NY	5.82	0.0	0.46	39.9	1.29	57.36	0.0	622.42	23.81	2.80	623.78
Denver, CO	8.21	3.91	5.71	0.0	0.04	17.15	72.99	1898.7	22.66	29.21	1906.2
US Averages	6.5	6.17	2.68	19.6	1.02	23.97	44.77	1232.3	24.14	18.26	1238.5

Tank-to-wheel: use phase modeling.

The Tank-to-Wheel (TTW) considers the tailpipe emissions due to fuel consumption. The diesel fuel consumption value shown in Table 1 is based on the EPA's Fuel Economy estimates [21]. According to the EPA [46], the amount of tailpipe carbon dioxide emitted from burning one gallon of diesel is 10,180 grams of CO_2. In 2011, the EPA estimated at 0.988 the ratio of CO_2 emissions to total GHG emissions, in order to express carbon dioxide, methane, and nitrous oxide as carbon dioxide equivalents [47]. Therefore CO_2e emissions are estimated as 22.72 lbs. CO_2e/gallon of diesel.

The electric tricycle fuel economy should be calculated by measuring battery energy capacity (in watt-hour) before and after a typical route of which distance is known. Since these measurements should be made for the batteries not for the electric motor, electricity losses as a result of batteries energy inefficiency are included in this factor. However, using this procedure, efficiency losses in battery charging are not taken in account. Stevens [48] developed a test procedure to examine battery charging efficiency as a function of battery state of charge (SOC). Results indicate that from 0% SOC to 84 % SOC the average overall efficiency is 91%, and that from upper 84% SOC

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the incremental efficiency is only 55%. Overall, an efficiency level of 85% is often assumed. In this study, we assume a charging efficiency level of 70% with the aim to not overstate tricycle's fuel efficiency.

Hence, the use phase GHG emissions per mile [lbs/mile] are calculated for each vehicle using the following equations: [1] for electric tricycles and [2] for diesel commercial vans.

$$\frac{CO_2e}{mile} = \frac{kWh}{mile} \times \left(\frac{ERg}{1 - GGL} \times \frac{1}{\eta}\right) \quad [1]$$

$$\frac{CO_2e}{VMT} = \frac{1}{mpg} \times \left(\frac{CO_2e_{tailpipe}}{gallon} + \frac{CO_2e_{upstream}}{gallon}\right) \quad [2]$$

VMT = vehicle miles traveled
ERg = eGRID generation based output Emission Rate [lbs. / kWh]
GGL = eGRID grid gross loss factor [decimal]
η = charging efficiency [decimal]

CASE STUDY

A case study was conducted using real-world data from Portland, OR to investigate the GHG emissions savings. This was done through the use a tricycle logistics service. Portland is known as one of the most bike-friendly cities in US. There are many bike paths throughout the city, which makes biking convenient. In addition, the Portland downtown area is relatively flat. That being the case, companies like B-Line can thrive. B-Line Sustainable Urban Delivery [16] was founded in February of 2009. The company delivers a wide variety of products, such as produce, baked goods, coffee beans, bike parts, and office supplies. They deliver to restaurants, coffeehouses, bike shops and other business through the use of electric and human powered cargo tricycles. Most of the B-Line customers are located throughout Portland's downtown area, as shown in Figure 1.

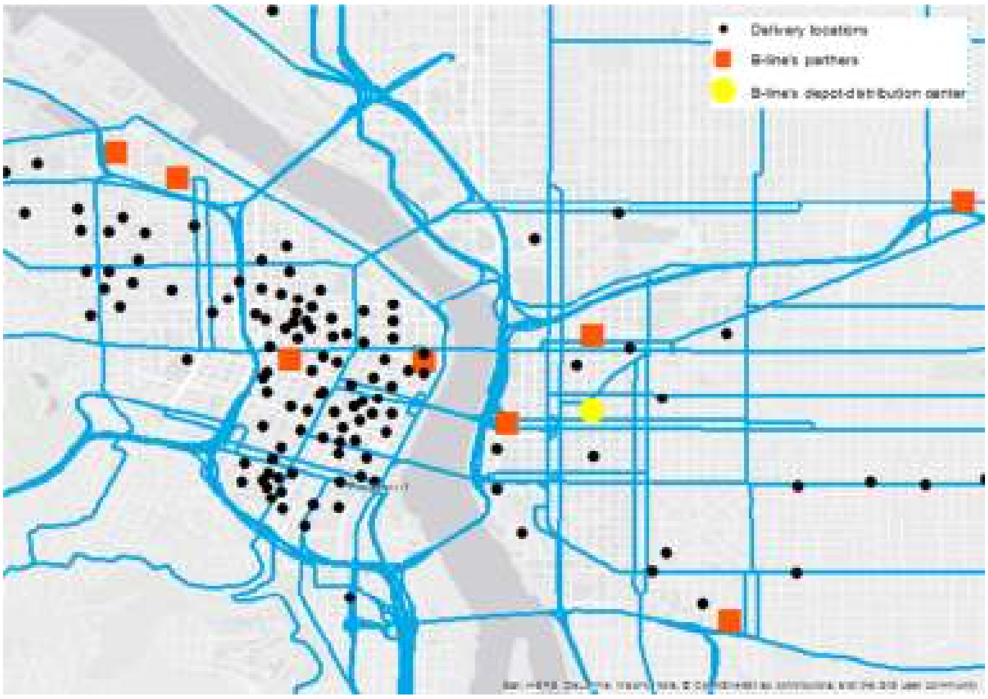

FIGURE 1 Partners and customers distribution of B-Line in Portland.

B-Line's distribution warehouse, is located in the Eastside, only 2 miles from downtown Portland. Since the company is near the edge of downtown, it could be considered as an Urban Distribution Center. B-Line currently provides delivery services for eight companies. Two of its major partners transport their products from their respective warehouses to B-Line's distribution center every morning between 6am and 9am. Two other companies transport goods once a week. The remaining four partners are located in or close to downtown, thus B-Line picks-up products of their locations and distribute to final customers. Usually, B-Line work 365 days a year. Routing at B-Line is complex because it involves traditional distribution from the depot with time windows but also intermediate pick-up at other partners' and customers' locations and delivery of those goods. In addition, the backhaul is in many cases utilized to consolidate (bring back to the B-Line depot) waste material for recycling. As many other urban delivery companies, B-Line provides both forward and reverse logistics services.

On May 2015, we were able to shadow B-Line Logistics Company. The data that was recorded and analyzed includes several days of detailed B-Line GPS routes and warehouse operations. The following average data is provided:

- Customer demand weight: 65 lbs.
- Service time: 10 min.
- Daily number of customers: 80 customers.
- Total distance traveled: 82 miles
- Tricycle traveling speed: 7.4 mph

B-Line owns 6 tricycles, along with 12 Lead Acid AGM batteries that weigh 77.8 lbs. each. Two batteries are needed for each tricycle. During a tricycle's route, one battery is in use, while the other is waiting at B-Line distribution center ready to be swapped. This is done to avoid low State-of-Charge (SOC), resulting in battery damage, which then can reduce life expectancy. Battery charger impacts were excluded from this assessment, because of their low weight and consequently insignificant impact on GHG emissions. The electric tricycle fuel economy was calculated based on B-Line's private information. During more than two years, B-Line staff have measured batteries parameters before and after each route. The company has more than 1150 measurements of all of its batteries, from which we calculated a fuel economy median of 48.65 watt-hour/mile. B-Line Carbon footprint can be calculated using the previous data. Using the data we collected from B-Line, we created two hypothetical scenarios to analyze the boundary emissions benefits of B-Line in comparison with a traditional diesel powered fleet.

Scenario 1 (consolidation factor = 1): In the best-case, B-Line would provide the same services as it does now but instead of using tricycles, it utilizes diesel vans.

Scenario 2 (consolidation factor = 0): In the worst-case, B-Line would not exist. Hence, each B-Line partner has its own commercial van for its logistics operations.

Given the pickup and delivery locations of each day, the researchers, together with B-Line operations manager, created hypothetical routes minimizing the global distance traveled for each scenario. As stated in the literature review, service time per customer using a van is likely to be greater than service time using a tricycle. This is due to the fact that tricycles can park on sidewalks while cargo vans have to find a secure location to park. Since 80 deliveries must be complied per day, and it is further assumed 10 minutes service time per customer, at least two vans are necessary to provide the same level of service in scenario 1. In scenario 2, it is assumed that each B-Line partner needs only one commercial van. In both scenarios not time windows or capacity constraints are assumed. This is due to the fact that commercial vans payload is much greater than tricycle payload. The result of minimizing distance is an average of 36 miles per day for the first scenario. In the second scenario one van coming from each partner's depot, makes its own deliveries and comes back to its depot. This results in 88 miles per day.

These calculations was taken within a conservative approach on an attempt to not underestimate a van's benefits in terms of distance traveled. To that end, neither logistics constraints are assumed, nor distance penalty to find a parking spot when making deliveries in downtown. Using the data from these two scenarios, we can calculate carbon footprint. Therefore, a comparison between B-Line's actual carbon footprint, against the footprint of a traditional diesel van delivery company can be made. That being said, important issues need to be highlighted.

1. As stated in the methodology section, Carbon Footprint assessment, using GHG Protocol Scope 3, should also include all indirect emissions. This implies that GHG emissions caused by B-Line partners, while transporting goods from their respective warehouses to B-Line's depot, should be taken into account. In this approach, B-Line's partners' vehicles life cycle emissions were not considered. Only life cycle GHG emissions associated to the fuel consumed are included. From the eight partners B-Line currently delivers for, only two bring their products to B-Line' distribution center. It is calculated that on average, the daily distance covered by B-Line's partners, from their depots to the B-Line distribution center, is 25 miles. That should be taken into account to assess B-Line's carbon footprint, as well as in

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scenario 1. We assume B-Line's partners use a 15 mpg diesel van for covering those 25 miles.

2. The life expectancy of common delivery vehicles is approximately 12 years [49]. Nevertheless, the life expectancy of freight tricycles is usually shorter and it is assumed to be 5 years.
3. Life expectancy of Lead-Acid AGM batteries is between 3-10 years depending on use. Here it is assumed 4.
4. Warehouse life cycle GHG emissions impacts are not included in this comparison. This is due to the fact that it is assumed that these facilities (space for loading and unloading, storage, park up vehicles overnight and walk-in cooler) are similar for both B-Line actual and scenario 1. This is a conservative approach because diesel vans are larger than tricycles, thus more space is needed to park overnight and to load/unload cargo.

RESULTS

This section present the results of the B-Line GHG emissions assessment compared against the GHG emissions of traditional pick-up and delivery companies in the two boundary scenarios. Scenario 1 is the best-case: cargo is consolidated in B-Line distribution center and then delivered using diesel vans. Scenario 2, the worst-case, cargo is dispersed and each company has its own commercial van for its logistics operations.

Figure 2 shows that CO_2e emissions as a result of tricycle delivery system fall between 51% and 72%, depending on the cargo consolidation factor. That is using the Portland electricity emissions rate. However, large emissions savings can be appreciated even in the case of carbon-intensive electricity generation, where GHG emissions are reduced by at least 46%. However, distance traveled increase substantially. As has been stated, B-Line daily mileage account for 82 miles, plus 25 miles covered by its partners. If B-Line service were provided with vans, they would travel 36 miles. That results in a reduction of 50% of miles traveled, but vans travel in congested streets or freeways and hence the overall impact is not a reduction in CO2 emissions for the traditional diesel company.

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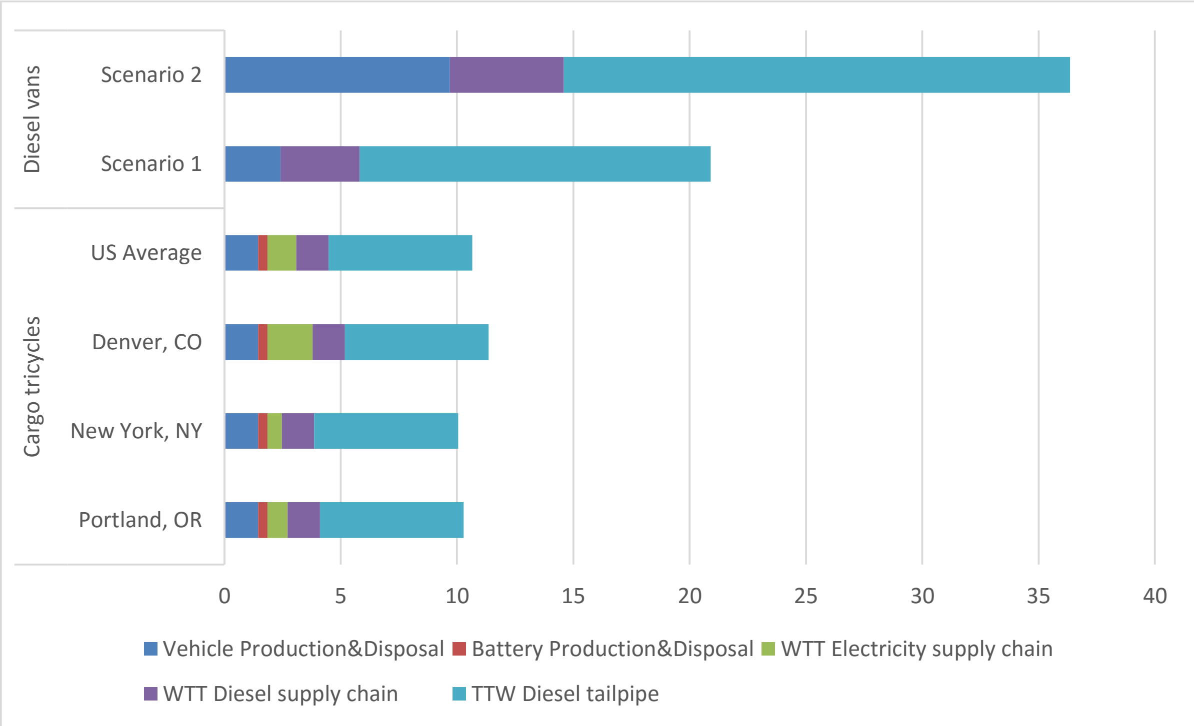

FIGURE 2 CO_2e emissions / year [metric tons]

B-Line avoids between 10 and 26 tons of CO2 emissions per year. However, most of GHG emissions are caused by B-Line partners while transporting goods from their respective warehouses to B-Line's depot. These 25 miles per day account for more than 64% of the B-Line GHG emissions. If in our approach, we account for all indirect emissions from consumption of purchased fuels and electricity, transmissions and distribution losses, vehicle production and disposal, but we do not consider emissions from B-Line's partners operations, a greater difference between a tricycle logistics company and a traditional one could be achieved.

Figure 3 shows CO_2e emissions per delivery. The impact of partners' emissions on B-Line's carbon footprint can be observed. If partner's transport activities are not included, a huge reduction can be appreciated: 6 tricycles and 12 batteries have 80% less environmental impact in terms of CO2e emissions than 2 common diesel cargo vans. Moreover, if partners' transport activities are not included, variations between different electricity generation profiles can be observed. For instance, if B-Line were operating in Denver, it would emit 28% more GHG emissions. If there were two companies like B-Line one in Denver and the other in New York City, that one operating in Denver would emit 35% more GHG emissions than its counterpart.

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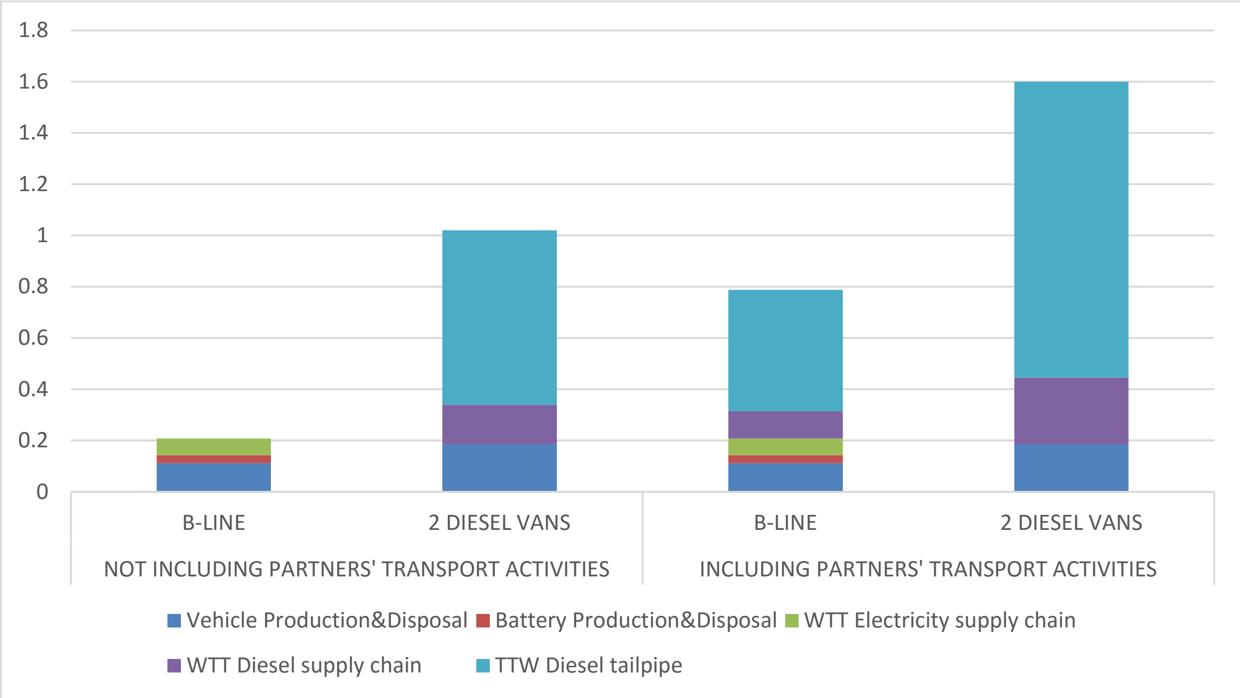

FIGURE 3 CO2e emissions / delivery [lbs.]

DISCUSSION AND CONCLUSIONS

A conservative approach has been taken in order to not overstate emissions savings. Diesel van fuel economy, a key variable, is often lower than 15mpg when operating in congested urban areas. Moreover, extra distance traveled searching and finding a parking (and the resulting emissions) are not considered. Nor are taken into account emissions resulting from idling while waiting for a parking spot or when double-parking although these emissions are significant [14].

Despite the conservative approach, the results show a high reduction of greenhouse gas emissions by replacing diesel vans with electric tricycles. Using Portland electricity mix, CO_2e emissions fell by at least 51%. But even in a region with a large electricity emission rate, CO_2e emissions are cut by half compared to traditional delivery vehicles. These emissions reductions are similar to other research efforts. Browne et al. [15] evaluated the use of an urban distribution center and electric vehicles in London and came to the same conclusion. CO_2e emissions were cut by a 54%. High urban density and congestion levels are important factors because in these conditions traffic speed and miles per gallon are reduced, emissions and route time increased, which can lead to diesel commercial vehicle fleets. In dense congested areas where freight transportation externalities are high, tricycle competitiveness and benefits are maximized. Due to the fact that tricycles service time is shorter but their speed is lower, they are more efficient when customers are more densely located. To minimize CO_2e per parcel capacity inefficiencies must be eradicated. Hence, urban consolidation centers are needed on the edge of downtown to switch cargo from trucks to tricycles o small electric vehicles.

State and local governments which are concerned about sustainability, public health and livability should incentivize the use of small electric freight vehicles. Tax breaks and other incentives like exclusive delivery zones and large pedestrian areas can tip the economic balance in favor of small electric vehicles. In this research only GHG emissions are analyzed, but is important to highlight the contribution of cargo tricycles to the overall reduction of air pollution. Tricycles can improve cities' air quality, not only because their lack of tailpipe emissions, but also because emissions are shifted to remote power plants.

In summary, this research has analyzed the carbon footprint of a tricycle logistics company and compared the results with the carbon footprint of a typical diesel powered delivery company. The results show that electric tricycles can reduce CO2e emissions between a 50% and 70% depending on the cargo consolidation factor. The evaluation has also shown that electricity emission profile have negligible impact on the overall life cycle emissions.

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ACKNOWLEDGEMENTS
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Anexo II. Metrans I-Nuf Paper

Sáenz, J., Figliozzi, M.A., Faulin, J., "Analysis of tricycle logistics services lifecycle GHG emissions", 6th METRANS International Urban Freight Conference, October 21-23, 2015, The Westing Long Beach Hotel, CA.(https://www.metrans.org/2015-i-nuf-overview)

ANALYSIS OF TRICYCLE LOGISTICS SERVICES LIFECYCLE GHG EMISSIONS

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Word count: 6060 + (2 tables and 3 figures) * 250 = 7310 words + 49 references.

ABSTRACT

This paper assesses the carbon footprint of a tricycle logistics company (B-Line) which is currently providing last mile distribution services in downtown Portland, Oregon. B-Line freight tricycles are electric and human powered vehicles with zero tailpipe emissions. Detailed real-world route GPS and warehouse data were recorded to evaluate B-Line supply chain operations and compare tricycle and diesel van emissions. Supply chain data is utilized to construct a lifecycle emissions model that includes power and fuel consumption during deliveries as well as vehicle and battery production, assembly and disposal emissions. The model also incorporates delivery logistics constraints such as time windows, cargo capacity, and customer distribution. Total emissions upper and lower bounds as well as elasticity values are analyzed. Results show that lifecycle emissions per delivery are at least five times lower when tricycles are utilized.

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INTRODUCTION

Our earth is warming. According to the EPA (USEPA, 2015a), the earth average temperature has increased by 1.5°F over the past hundred years and this increase is likely due to anthropogenic greenhouse gas (GHG) emissions. EPA projections estimate that the earth temperature will increase between 2 and 11.5°F over this century.

Greenhouse gas emissions from transportation accounted for 27% of total U.S.A. GHG emissions in 2013, and have risen by 16% since 1990. Reducing global transport GHG emissions will be challenging because transportation emissions are strongly coupled with gross domestic product (GDP) growth. Since 2008, truck vehicle miles traveled (VMT) in the U.S. has been increasing as a result of economic growth, more international trade, and more intercity trade (NCFRP, 2013). In 2006, freight movements accounted for 9% of the total U.S. greenhouse gas emissions and 29% of the total GHG emissions coming from transportation-related sources; truck emissions accounted for 68% of this total. Trucking emissions are caused by VMTs but also by idling. Idling is ubiquitous at ports and intermodal stations as well as inner city streets as a result of traffic congestion and during deliveries; idling trucks in the U.S.A. consume about 20 million barrels of diesel fuel and generate 10 million tons of CO_2 annually (Cambridge Systematics, 2010).

Traffic congestion has a great impact on fuel efficiency and CO2 emissions because of the relationship between vehicle operating speed and the rate of CO2 per mile traveled. Delivery fleet emissions are linked to distance traveled but also show a rapid non-lineal growth in emissions when speed falls below 30 mph (Figliozzi, 2010). Congestion affect emission rates because fuel consumption is a function of both acceleration rates and travel speeds. A strategy to reduce transportation emissions is switch to vehicles with a smaller carbon footprint. Environmental advocates, policy-makers and the trucking industry have great expectations for use of electric commercial vehicles in urban freight movement. Emissions reductions are expected to be high, especially in areas with low speed, high congestion, and high idling rates during deliveries and the last mile of transportation. Smaller vehicles (tricycles) have a smaller production and disposal carbon footprint (USDOE, 2015) but the tradeoffs are not so clear when several smaller vehicles can be replaced by a larger vehicle (e.g. diesel vans). This research analyzes the level of GHG emissions reductions that can be achieved utilizing electric tricycles in urban areas. B-Line (2015) is a sustainable logistics company that is currently operating in downtown Portland, Oregon. B-Line offers customers an urban delivery as well as warehousing and pick-up services. The researchers were able to shadow B-Line drivers, warehouse staff, and mechanics. Several days of detailed GPS route and warehouse data were recorded and filmed/photographed. The main goal of this study is to compare B-Line's lifecycle GHG emissions against lifecycle GHG emissions of a conventional urban delivery company that utilizes diesel vans. Diesel vans are the natural competitor for tricycles given relative small tricycle capacity. Although several research efforts have recently evaluated the benefits of tricycle logistics services, most research efforts have ignored vehicle life cycle emissions when evaluating environmental impacts. The existing research have mainly focused on operational CO_2 emissions. To the best of the authors' knowledge, there is no published tricycle logistics company lifecycle GHG assessments in the existing literature or analyzing emissions elasticity values.

LITERATURE REVIEW

A strategy to reduce urban truck traffic is the utilization of urban consolidation centers which seek to remove freight vehicles by finding ways to combine the pick-ups and deliveries of different shippers and different receivers (Dablanc et al., 2013). Urban consolidation centers and companies which provide last mile logistics by using electric vehicles and/or tricycles have been increasingly appearing in European cities (Schiliwa et al. 2015).

A study documents the benefits of the Chronopost Concorde urban consolidation center located in downtown Paris (TURBLOG, 2011). Chronopost is a big French express parcel company and the Chronopost Concorde facility is an urban depot where deliveries are first trucked and later moved to electric vehicles for last-mile delivery; a fleet of 16 electric vehicles is utilized for final deliveries to clients. Chronopost achieved higher productivity, 70 deliveries per route instead of 56, and CO2 emissions decreased by 60% in a six-month period. One-third of the decrease was due to the new logistics organization and two-thirds of the reduction was due to the use of an electric van fleet for final deliveries. Browne et al (2011) evaluated a trial in which office supply was delivered from a suburban London depot to final customers in downtown. During the trial diesel vans were replaced by electric vans and tricycles operated from a consolidation center close to downtown. Deliveries are first trucked and later moved to electric vehicles for last-mile delivery in downtown London. A total of six tricycles and three electric vans delivered the cargo from the distribution center to final customers. The operation of these electric vehicles did not result in any fossil fuel consumption or GHG emissions because the electricity used by these electric vehicles was produced from renewable sources. The result showed great benefits; total distance travelled was reduced by 20% and the CO2e emissions per parcel fell by 54%. GNewt Cargo was the operator of the micro-consolidation center, tricycles, and electric vans.

Conway et al. (2014) analyzed two tricycle delivery services in New York City. Emissions reductions were estimated assuming that Cycles Maximus cargo tricycles replaced a five-year-old cargo van. The annual savings were between 19 and 21 tons of CO_2, and between 3.4 and 4 lbs. of PM10. In this case study, tricycles were fully human-powered and therefore no emissions are released during their operation. The emissions savings were estimated by using the EPA's MOVES model.

Unlike previous research efforts, this research analyzes all lifecycle stages of tricycles and vans and also utilizes a highly detailed dataset obtained from shadowing real-world operations of a tricycle logistics company. In addition, a logistic model based on continuous approximations is created and emissions elasticity values are estimated and analyzed.

CASE STUDY

B-Line Sustainable Urban Delivery was founded in February of 2009. The company delivers a wide variety of products, such as produce, baked goods, coffee beans, bike parts, and office supplies to restaurants, coffeehouses, bike shops and office buildings. B-line also performs reverse logistic services with the pickup and consolidation of materials for recycling. B-Line only utilizes electric and human powered cargo tricycles for delivery and pickups. Most of the B-Line customers are located in or nearby Portland downtown area. B-Line distribution warehouse is located only 2 miles from downtown Portland as shown in Figure 1.

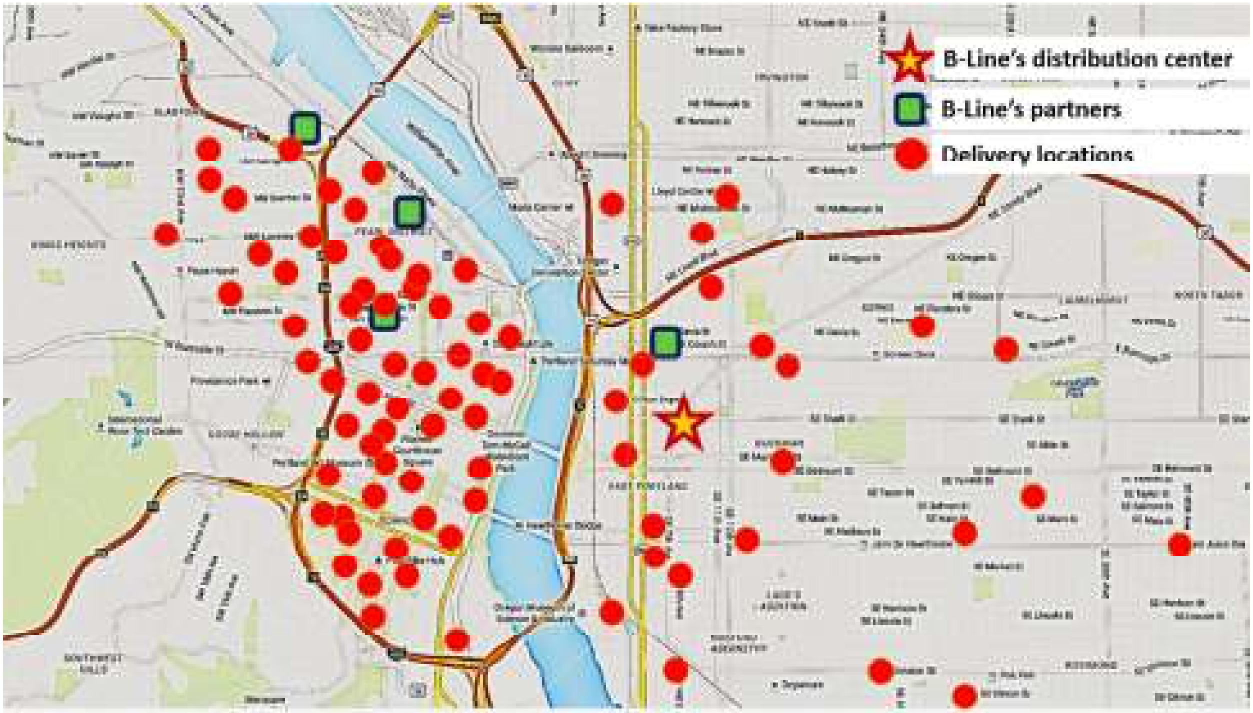

FIGURE 1. B-Line distribution warehouse, partners and customers location in downtown Portland.

B-Line depot is located near the edge of downtown and can be considered as an urban consolidation and distribution center. B-Line routes are complex because tricycles volume optimization is essential to achieve competitiveness. Routes not only include traditional distribution from the depot with time windows but also pickup at partners and customers locations. Routes may include both pickup(s) and deliveries.

This research only considers the distribution of goods delivered from B-Line's depot to customers, approximately 90% of the products delivered. For the sake of brevity and to facilitate the comparison of the results with previous research efforts, this research does not analyze the benefits and/or GHG emissions reductions of reverse logistic services for the pickup and consolidation of materials for recycling.

B-Line's partners transport their products from their respective warehouses to B-Line's depot and then B-Line delivers those products by tricycle. B-line operates seven days per week. On May 2015, the researchers were able to collect detailed route and warehouse/depot operations data. Detailed vehicle and batteries data was provided by the full-time mechanic at the depot. Partners operations and warehousing consolidation data was provided by the operations manager. Several days of detailed GPS route data was recorded utilizing a smartphone application called ORcycle (http://www.pdx.edu/transportation-lab/orcycle). The GPS data was then mapped and analyzed to estimate route durations, tricycle speeds, and customer service times. Table 1 presents a summary of some key average values that describe the scope of B-Line operations.

Characteristic or Parameter	**B-Line delivery system**
Number of daily deliveries	80
Delivery area size (mi2)	8 sq. miles
Distance from warehouse (mi)	2 miles
Customer demand (lb.)	65 lbs.
Working hours (h)	8 hours
Total distance traveled per day	82 miles
Customer service time (min)	10 minutes
Delivery days per year	360 days

TABLE 1. Delivery service characteristics and planning parameters.

B-Line owns 6 tricycles made by Cycles Maximus and 12 Lead Acid AMG batteries made by Odyssey Battery. Two batteries are needed for each tricycle; one for the morning route and one for an afternoon route. Batteries are swapped after a route to ensure that batteries do not

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reach a low state-of-charge which may result in reduced battery life. During several years B-Line staff have collected 1,150 observations related battery energy parameters before and after each route. Utilizing this data, we estimated a median fuel economy of 48.65 watt-hour/mile (20.55 miles/kWh). These measurements were taken from the batteries themselves (not from the electric motor) and electricity losses as a result of batteries energy transmission inefficiency are included in this median number. In addition, chargers and power converters connected to the grid are drain small amounts of power and there are some efficiency losses when the battery is charging; an efficiency level of 85% is typical in the literature (Stevens and Corey, 1996). In this study, we assume an average charging efficiency level of 70% in order to avoid over-estimating tricycle's fuel efficiency. Battery chargers life-cycle impacts (materials, production, assembly and recycling) are excluded from this assessment, because of their small number, low weight and long life expectancy.

The goal of this research is to compare lifecycle GHG emissions of tricycles and conventional diesel vans. The specifications of a typical cargo tricycle and the assumed values for a diesel van are shown in Table 2.

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Specification	Electric tricycle Cycles Maximus	Diesel cargo van RAM ProMaster 2500
Gross Vehicle Weight Rate	1,100 lbs.	8,941 lbs.
Curb Weight	500 lbs.	4,781 lbs.
Battery Weight	77.8 lbs.	-
Engine Capacity	-	3.6 liter V-6
$e_{vehicle\ material}$	4.108 lbs CO2e / lbs vehicle	3.995 lbs CO2e / lbs vehicle
$e_{assembly+disposal+recycling}$	1.247 lbs CO2e / lbs vehicle	1.247 lbs CO2e / lbs vehicle
$e_{battery}$	3.93 lbs CO2e / lbs battery	-
$e_{well-to-tank}$	0.846 lbs CO2e / kWh	5.108 lbs CO2e / gallon
$e_{tank-to-wheel}$	-	22.72 lbs CO2e / gallon
Charger efficiency	0.7	-
Max Payload	600 lbs.	4,160 lbs.
Range	30 miles	465 miles
Fuel economy (city)	48.65 watt-hour/mile	18 mpg
Fuel economy (find a parking)	-	8 mpg
Idle fuel consumption	-	0.57 gallon / hour
Life time (years)	5 years	12 years
Distance to find parking (ft.)	0 ft.	200 ft.
Time to find parking (min)	0 min	3 min
Average speed inside service area	7 mph	10 mph
Average speed outside service area	7 mph	30 mph

TABLE 2. Vehicle characteristics and emissions parameters.

LIFECYCLE ASSESSMENT OF VEHICLES

Life cycle assessment (LCA) is also known as a 'cradle-to-grave' assessment. LCA separates emissions along life cycle phases: extraction of raw materials from the earth, process of those materials, manufacturing, distribution, product use and disposal or recycling at the end. We examine commercial vans and electric tricycles in three distinct phases: (a) vehicle cycle, from raw material extraction to disposal but without considering vehicle utilization; (b) well-to-tank or the lifecycle of fuel/electricity production and distribution; and (c) tank-to-wheel or vehicle use operation. This section focuses on the vehicle cycle assessment (a) that does not includes vehicle utilization.

Vehicle production and disposal includes: extraction of raw materials, transport to factories where alloys are developed and final materials are produced, transportation of these

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parts to assembly plants, production of vehicles at assembly factories, transport and distribution of vehicles to dealers and then, after the use phase, disposal or recycling of vehicles. GHG emissions of these stages are estimated using the GREET model which uses vehicle weight as the functional unit (USDOE, 2015). The GREET model contains hundreds of parameters with default values based on national/regional statics or industrial practice. Detailed documentation of assumptions in relation to industrial processes and technologies are available on GREET publications (USDOE, 2015).

The GREET model does not include the e-tricycle vehicle type, hence, the electric tricycle was modeled as an electric vehicle pick-up truck with conventional materials. The conventional diesel van was modeled as a pick-up truck with an internal combustion engine and conventional materials. Vehicles weight and vehicle production, materials and disposal emissions rates are shown in Table 1.

Additional batteries are necessary for the tricycles operation. Electric tricycles utilize Valve-Regulated Lead-Acid (VRLA) batteries and the estimated the life-cycle emissions of producing VRLA batteries was taken from Sullivan and Gaines (2010). The emissions associated to batteries recycling or disposal stage was taken from Rantik (1999). Combining these sources, it is estimated that battery lifecycle GHG emissions are 3.93 kgCO2e/kg. Battery weight and emissions rate are shown in Table 1.

LIFECYCLE ASSESSMENT OF ENERGY SOURCES

This is the well-to-tank (WTT) analysis of emissions that includes all the emissions in the energy supply chain. The diesel and the electricity supply chains are analyzed individually.

Life-cycle GHG emissions for fuels such as diesel include several stages: petroleum pumping and extracting, transporting to refineries, production of the final diesel fuel, and then dispensing and distributing through to diesel stations. Around 20% of the diesel life-cycle emissions are emitted during these well-to-tank processes. Using the GREET model and gallons of diesel as the functional unit, the diesel GHG emission factor is estimated and shown in Table 2.

Although electric tricycles do not produce direct emissions, greenhouse gas emissions from electricity generation may be substantial. Electric vehicles produce emissions at power plants where electricity has been generated. Emissions factors are taken from the eGRID database that includes transmission and distribution losses (USEPA, 2015b). The eGRID output emission rates and grid gross loss factor which accounts for transmission and distribution losses are shown in Table 3. The electric generation profiles of three U.S. cities are shown. New York has the “greenest” electricity generation in terms of CO2e, Denver has the “dirtiest”. Portland is below the USA average.

Region	GGL Factor (%)	Hydro (%)	Other renewable (%)	Nuclear (%)	Oil (%)	Gas (%)	Coal (%)	CO2e Emitted lbs./MWh
Portland, OR	8.21	43.55	5.54	3.44	0.32	14.34	31.3	847.0
New York, NY	5.82	0.0	0.46	39.9	1.29	57.36	0.0	623.8
Denver, CO	8.21	3.91	5.71	0.0	0.04	17.15	72.99	1906.2
USA Average	6.5	6.17	2.68	19.6	1.02	23.97	44.77	1238.5

TABLE 3. Energy sources, grid gross loss (GGL), and CO2e emissions. Source: US EPA

LIFECYCLE ASSESSMENT OF VEHICLE UTILIZATION

This is the tank-to-wheel (TTW) or utilization phase. The vast majority of life-cycle GHG emissions are emitted during the use phase. In this study emissions related to vehicle maintenance are omitted because their value is negligible comparison with other life-cycle stages. A fuel economy of 18 miles per gallon is assumed during urban delivery operations, as shown in Table 2. According to EPA (2014), emissions are estimated to be 22.72 lbs. CO_2e/gallon of diesel. The amount of emissions in the utilization phase is a function of gallons consumed or distance traveled and fuel efficiency.

A continuous approximation model can be used to estimate total distance traveled by introducing logistics constraints. Dangazo (1984) proposed an approximation for capacitated vehicle routing problems (CVRP) and Figliozzi (2008) modified the approximation model for routes with a few customers per route. Tipagornwong and Figliozzi (2014) modified the approximation model to incorporate specific characteristics of tricycles. For instance, tricycles can deliver faster than traditional vehicles because they can be parked legally on sidewalks in front of the delivery location. In contrast, conventional vehicles need to spend time and distance to find and an available parking space. A new term was added to account for distance to find an empty parking space. The distance approximation is the following:

$$VRP = k_1 \frac{n-m}{n}\sqrt{nA} + 2\bar{r}m + n \cdot l_{park}$$

where

- VRP = distance traveled for a fleet of vehicles (km);
- $\bar{r}$ = distance between service area and a depot (km);
- n = number of customers;
- C = capacity of a vehicle (number of customer visits per vehicle);

- $m =$ number of vehicles,
- $A =$ size of service area (km^2)
- $k_1 =$ customer distribution coefficient.
- l_{park} = average distance to find a parking space.

The parameter k_1 accounts for customers' location distribution and is a function of customers' density. Values of the k_1 coefficient can be calibrated empirically to the delivery service area; in this research the coefficient was calibrated to mimic B-Line's operation in terms of average daily total distance (82 miles), nine routes and five vehicles.

Access to parking turns out to be a key variable to estimate emissions. In this research it is assumed that the driver of a delivery van have to either (i) cruise to find a free parking space or (ii) double-park illegally in front of the delivery destination. In case (i) there are additional emissions due the the additional distance traveled and also a time penalty is added to the route time; penalties of 200 feet and 3 minutes are assumed respectively. It is further assumed a fuel efficiency of 8 mpg due to the low speed while searching for parking, as shown in Table 2. In case (ii) there are additional emissions because the vehicle is idling while the customer is serviced. Distance and time penalty terms are not included, but a new term accounting for idle emissions is added directly into the emissions model. The estimated fuel consumption of an idling engine is 0.6 liters / hour per liter of engine displacement (Ecomobile, 2015). Hence, a 3.6 liter engine consumes 0.57 gallons / hour, as shown in Table 2.

EMISSIONS AND LOGISTICS MODEL

Unlike previous research efforts, the model presented in this research include all stages in vehicle production and recycling and also incorporates logistics restrictions (delivery time, cargo, customer distribution) and parking characteristics of tricycles and vans. In addition, due to the small size and payload of electric tricycles, more than one tricycle can be replaced by a diesel delivery van. Hence, it is necessary to estimate what is is the number of vans that minimizes lifecycle emissions for this vehicle type.

The model presented in this section was utilized to estimate the number of vans that minimizes lifecycle emissions while satisfying all the logistics constrains that B-line vehicles must meet. The lifecycle emissions model is presented below. As explained in the previous section, B-line tricycle data was utilized to calibrate the parameter k_1.

SET

$I =$ Set of vehicle types, i belongs to the set of vehicle types, I ={van, tricycle}

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DECISION VARIABLES

$R^i =$ Number of routes of vehicle i to serve all customers

PARAMETERS

$E^i_{tot} =$ Total emissions for vehicle i (lbs.CO_2e)

$e^i_{mat} =$ Emissions of material processing for vehicle i (lbs.CO_2e / lbs. vehicle)

$e^i_{prod} =$ Emissions of vehicle i production / disposal (lbs.CO_2e / lbs. vehicle)

$e^i_{bat} =$ Emissions of battery production / disposal (lbs.CO_2e / lbs. battery)

$e^i_{wtt} =$ Emissions of WTT phase for vehicle i (lbs.CO_2e / gallon or lbs.CO2e / kWh)

$e^i_{ttw} =$ Emissions of TTW phase for vehicle i (lbs.CO_2e / gallon or lbs.CO2e / kWh)

OTHER PARAMETERS

$c^i =$ Per – mile fuel or electricity consumed by vehicle i (mile / gallon or mile / kWh)

$c_{park} =$ Per – mile fuel consumed while finding a parking (mile / gallon)

$c_{idle} =$ Per – hour fuel consumed at idle (gallon / hour)

$m^i =$ Number of vehicles of type i to serve all customers

$l^i =$ Per – tour distance traveled to serve route of vehicle type i (miles / tour)

$w^i_{tar} =$ Vehicle i tare weigh (lbs.)

$w^i_{bat} =$ Battery weigh (lbs.)

$b^i =$ Number of batteries

$w^i_{cap} =$ Payload capacity for vehicle i (lbs.)

$w_d =$ Average unit customer demand (lbs.)

$v^i_{in} =$ Average speed of vehicle i running inside service area (mph)

$v^i_{out} =$ Average speed of vehicle i running outside service area (mph)

$t^i =$ Total route time of vehicle i (hours)

$t^i_{ser} =$ Average customer service time from vehicle i (hours)

$t_{max} =$ Maximum daily working time (hours)

$y^i =$ Life expectancy of vehicle i (years)

$y^b =$ Life expectancy of batteries (years)

$d_{year} =$ Days of service per year

OBJECTIVE

Minimize total emissions = material assembly, production & disposal + battery material, production & disposal + use phase + find parking (only first scenario) + idle service time (only second scenario)

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$$E_{tot}^{i} = \frac{\left[\left(e_{mat}^{i} + e_{prod}^{i}\right)m^{i} \cdot w_{tar}^{i}\right]}{y^{i}} + \frac{d_{year}\left[e_{bat}^{i} \cdot b^{i} \cdot w_{bat}^{i}\right]}{y^{b}} + \frac{d_{year}\left(e_{wwt}^{i} + e_{ttw}^{i}\right)R^{i} \cdot l^{i}}{c^{i}} + h\frac{d_{year}\left(e_{wwt}^{i} + e_{ttw}^{i}\right)n \cdot l_{park}^{i}}{c_{park}} + jd_{year}\left(e_{wwt}^{i} + e_{ttw}^{i}\right)n \cdot t_{ser}^{i} \cdot c_{idle}$$

[1]

$$l^{i} = \frac{k_1 \frac{n - m^{i}}{n}\sqrt{nA}}{R^{i}} + 2\bar{r}$$

[2]

$$t^{i} = \frac{k_1 \frac{n - m^{i}}{n}\sqrt{nA}}{R^{i} \cdot v_{in}^{i}} + \frac{2\bar{r}}{v_{out}^{i}} + n \cdot t_{ser}^{i} + h \cdot n \cdot t_{park}^{i}$$

[3]

$$m^{i} \geq \frac{R^{i} \cdot t^{i}}{t_{max}}$$

[4]

Subject to

$$R^{i} \geq \frac{n \cdot w_d}{w_{cap}^{i}}$$

[5]

$t^{i} \leq t_{max}$ [6]

$b^{i} \geq 2m^{i}$ [7]

$R^{i} \in$ Set of positive integers (natural number) [8]

$m^{i} \in$ Set of positive integers (natural number) [9]

$h = 1$ For the first scenario, otherwise = 0 [10]

$j = 1$ For the second scenario, otherwise = 0 [11]

Equation 1 is the objective function. Equation 2 is the length of a route, starting from a depot, serving customers, and returning to the depot. Equation 3 is the duration of a vehicle route. Equation 4 is the minimum number of vehicles needed to serve all customers. Equation 5 is the vehicle route capacity. Equation 6 is the working time constraint. Equation 7 is the minimum number of batteries for a tricycle. Equations 8 and 9 restrict the number of vehicles and routes to the set of positive integers. Equations 10 and 11 make one scenario at a time.

MODELING RESULTS

Nine tricycle routes are needed to serve all customers: four tricycles make two routes and one tricycle just make one. On the other hand, three vans can serve all customers by doing just one route each. Even though the distance traveled by vans is smaller, the total emissions are several times higher. The total daily distance traveled by diesel vans is 63 miles (of which 3 miles are extra distance to find parking), almost a 25 percent less than the distance traveled by tricycles. Because of the tricycle's lower payload, a tricycle route has fewer deliveries and is shorter.

Figure 2 compares total emissions per customer in pounds of CO2e. The left columns represent lifecycle tricycle delivery emissions and the right columns lifecycle van delivery emissions. The third column represent van emissions when vans travel 200 ft to find parking; the fourth column represent van emissions when vans double park and idle. Tricycle lifecycle emissions are substantially lower than van lifecycle emissions. Even the emissions using "dirty" electricity are at least five times lower than van emissions. Utilizing Portland's electricity generation profile, tricycle emissions due to electricity consumption (operating emissions) only account for 28% of total tricycle emissions. The remaining 72 percent are due to tricycles and batteries production and recycling. Using Denver's electricity generation profile, operating emissions account for 47%. By contrast, in the case of diesel vans, operating emissions (due to fuel consumption) represent 82% of the total emissions in the first scenario, and more than 92% in the second scenario.

Idling can have a highly significant impact in urban logistics when the routes have many customers and customers are nearby; vehicles spend more time at the customers than actually traveling between customers. Because customers service time is 10 minutes on average a total of 4.5 hours of idling time per day per van was calculated.

Another important outcome of this study is that from the first time, to the best of the authors' knowledge, electricity consumption during electric-tricycles operations has been measured: 48.65 watt-hour per mile, or 20.55 miles per kilowatt-hour. Diesel vans fuel economy is assumed to be 18 miles per gallon. The EPA estimates that the energy content of one gallon of diesel is equivalent to 33.7 kWh, and that makes diesel fuel economy of 18 mpg equivalent to 0.53 miles per kilowatt-hour. This makes B-line tricycles almost 40 times more energy efficient than diesel vans.

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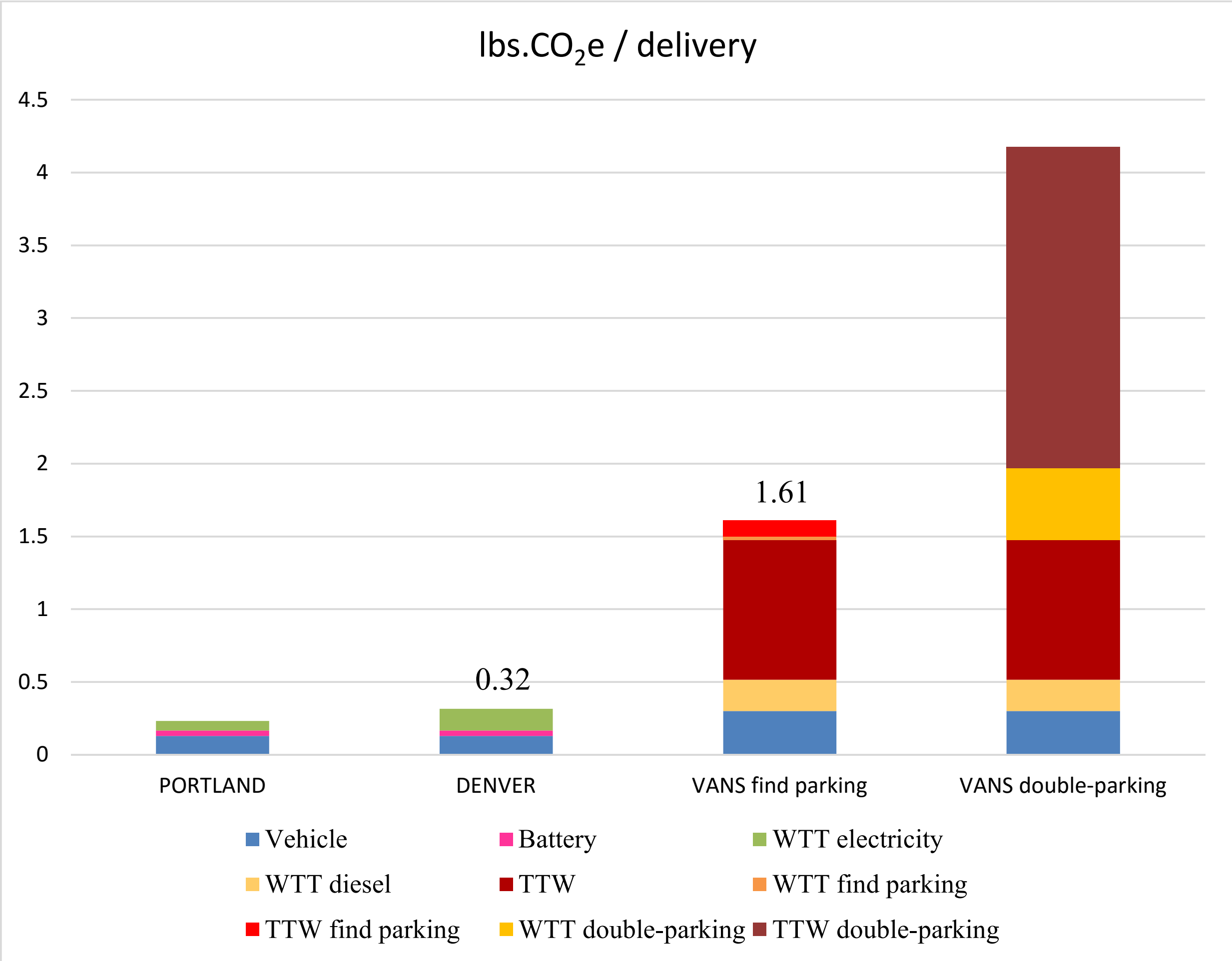

FIGURE 2 Emissions per customer in lbsCOe/customer

Elasticity Analysis of per customer emissions

An elasticity analysis is useful to understand what variables are likely to affect total lifetime emission changes. All parameters in the elasticity analysis are related to logistics and transportation constraints, as shown in Figure 4.

Emissions are very sensitive to number of customers or number of daily deliveries and customer distribution because these variable increases significantly the distance traveled. The emissions of vans are very sensitive to fuel efficiency but when vans double park (D-P) the elasticity value is almost 1/3 lower. When vans double park emissions are very sensitive to fuel consumption while idling and the service time duration. In general, any variable related to distance traveled affect more vans than tricycles, except for distance between depot and service area. Tricycles return more often to the depot (shorter routes), hence they are penalized for this additional distance.

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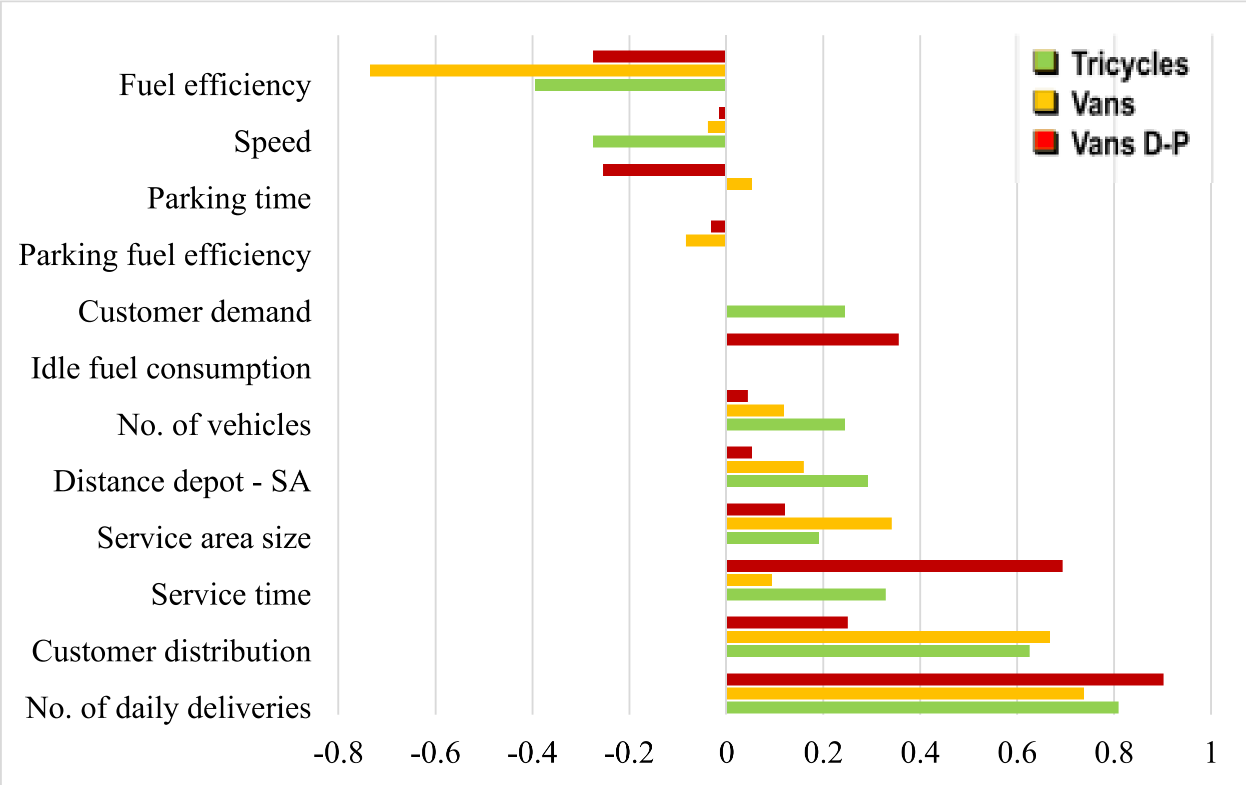

FIGURE 4. Per customer emissions elasticity analysis.

CONCLUSIONS

This research has analyzed the carbon footprint of a tricycle logistics company that is currently providing delivery services in Portland, Oregon. Results show that emissions per customer are at least 5 times smaller when tricycles are utilized. With Portland's electricity profile, tricycle lifecycle CO_2e emissions per customer are around seven times smaller than diesel vans lifecycle CO_2e emissions per customer. Utilizing the "dirtiest" USA electricity generation profile lifecycle CO_2e emissions per customer are five times smaller when tricycles are utilized.

High customer density is one of the most important variables to reduce emissions. Due to the fact that tricycles service time is shorter and their speed is lower, dense congested urban areas where transportation externalities are higher, maximize tricycles' environmental benefits. Higher congestion levels, lower road capacity, and extensive bicycle networks improve tricycle logistics services environmental benefits and competitiveness. Idling at customers can drastically increase vans emissions.

Local and state governments which are concerned about freight urban transportation externalities should incentive the use of small electric vehicles in urban delivery operations. On a per mile basis, tricycles have CO_2e emissions rates that are 40 times smaller than vans' CO_2e emission rates. In this study only greenhouse gases which affect global warming are estimated, but it is important to highlight the contribution of tricycles logistics services to improve cities' air quality by shifting tailpipe emissions from downtown areas to more remote power plants.

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